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SCHOLARLY RESEARCH PROGRAM

Delivery Order 0011: Concept Design for a 1 MW Generator Based on a Permanent Magnet Rotor (Turbine Driven)

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WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251

NOTICE

THIS TECHNICAL REPORT IS APPROVED FOR PUBLICATION.

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14. ABSTRACT
The final report documents a conceptual design for a generator capable of generating 1 MW electrical output at 200 VDC with a shaft speed of 15,000 rpm and a maximum outer diameter of 15 inches. It is based on an interior permanent magnet rotor configuration with three phase output. The designs were developed and analyzed using the PC-BDC software which is part of the SPEED (Scottish Power Electronics and Electric Drives consortium) motor/generator analysis suite.

Results indicate that the 1 MW generator would have an active magnetic weight of 158-300 lbms which would translate into a total machine weight of approximately 250 - 450 lbms. Thermal management of the designs was not analyzed in detail due to the limited scope of the project.

This effort was performed under a delivery order contract to Motorsoft; Universal Energy Systems was the contractor.

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generator, megawatt, electrical generator, electrical power, turbine, permanent magnet generator

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1.0 Introduction

The most significant difference between aerospace turbine driven generators or alternators as compared to conventional generators is high power density for the lowest possible weight. No matter which magnetic configuration is selected expensive high performance materials and perhaps even higher manufacturing cost within reason are minor considerations. Even a small savings in generator size as a result of using the best designs and materials can yield rapid paybacks by substantial fuel savings. In the case of certain unmanned airborne vehicles that use generators the lower generator weight yields increased payloads. The design of conventional generators is not based on these principles.

For these high power density machines there seems to be two categories of generators, KW machines and MW machines. For all types there are some historically common magnetic configurations.

A - Axial field (wound or PM)
B - Conventional wound radial field
C – Conventional surface PM rotor (developed by Gene Aha)
D - PM flux squeezing radial field (developed by Dr E. Richter & Dr. L.J. Bailey)
E - Claw-rotor with wound or OM field (common with automotive)
F - Homopolar

There has been much debate and design comparisons performed over the last 30 or more years as to which magnetic circuit configurations are the best choices for each application. A brief summary from the debaters to form some general conclusions is provided so we can get on with this conceptual design of a 1 MW generator.

The claw rotor type can be disregarded at once because several studies have shown that its output is 1.5 to 5 time worse than the best radial field configurations. These same studies show that the flux squeezing radial designs are the best for the smaller generators in the KW & up category. For the MW generator category the studies show that the conventional surface mounted magnet rotor types offer the highest power densities. These are difficult to control as compared to wound field machines with PM exciters but not impossible.

There is a newer type of PM machine that bears careful study that is known as an interior magnet machine that has its output power produced by two magnetic fields linking the stator phase windings. With the magnets of the surface mounted rotor placed just below the surface of the soft iron steel rotor core with soft iron completely over the magnet at the airgap part there exists a reluctance component of the output power. This can be thought of as a hybrid SR/PM synchronous generator. The permanent magnet pole arc and the soft iron poles between the magnets are critical in the design to achieve the balance between the Reluctance and the PM components of flux linkage. The output seems to be easily controlled by the adjustment of the angle between E (back emf) & V (output volts). This same sort of output control can be implemented with surface mounted magnets but not as effectively as with interior magnets. The flux linkage is much easier to change because the soft iron poles are isotropic and the flux can easily be moved tangentially in the poles to control flux linkage. This type of machine is currently being used by Toyota for the Prius hybrid automobile. The output power falls into the KW category. Perhaps some version of this interior magnet machine is worth considering for the MW size machines. (It is important to note that rpm and output power levels both are important considerations and usually drive the final design choices for the magnetic circuit selection.)

It is understood that WPAFB has issued contracts for more or less conventional 1 & 2 MW generators with wound field radial magnetic circuits. Therefore we have tried to optimize a surface mounted PM type, 1 MW generator using some of the processes developed by both Fisher and Motorsoft for the rotor and the stator construction. The goal was for the highest power density possible so the machine is of course assumed to be liquid cooled. The rotor is designed for a high number of poles to reduce the magnetic iron volume and weight required. The cross section of the stator yoke iron is cut in half each time the number of poles is doubled. The weight of heavy magnetic materials comes down rapidly with increasing number of poles. High pole machines are now technically feasible due to the advances in power semiconductors, high speed micro-processors such as DSP’s (digital signal processors) and low core loss lamination materials.

The stator design is based upon a lamination construction developed and patented by Fisher that allows the use of the best lamination materials to minimize the core losses and also eliminates wasted material from the stamping process. The stator would be epoxy encapsulated with the latest thermal conductive materials to improve the conduction of the heat sources to the cooling medium through a liquid cooling jacket.

2.0 Summary of Generator Requirements

2.1 Specified Design Goals

1. One megawatt output continuous @ rated speed

2. Three phase output or two three phase circuits

2. 200 VDC after FWBR (full wave bridge rectifier), fully loaded, thermally stable at operating temperature. (200 VDC =141.4 Vrms L-L)

3. Rated speed = 15,000 RPM

4. Liquid cooled (250 F incoming)

5. Maximum O.D. = 15 inches over frame

2.2 Assumptions Used for Design Concept

1. Radial air gap machine

2. Surface-magnet rare-earth PM alternator with external power conditioner. (2-17 Samarium Cobalt selected due to high temp. stability)

3. Aluminum frame / cooling jacket about 0.75 inches thick per side. (13.50" stator diameter.)

4. Best materials to be selected including insulation system

3.0 Summary of Initial Sizing of Design Concept

3.1. Rotor Diameter Selection

The larger the rotor diameter, the more torque that can be developed per axial length of active magnet, by approximately D^2. So the question is: “*What is the largest diameter rotor that can run at 15000 rpm?”*

The diameter is limited by the ability to retain the magnets. The ability to retain the magnets is limited by the strength and pre-stress of the material used for the retainment band.

A suitable nonmagnetic super alloy is chosen for this design which, when analyzed with our retainment ring program, dictates the following design based on allowed stress:

2 X 0.020” thick bands over 8.0 inch diameter magnets (0.040” thick)
Lift-off speed 16442 (must be greater than 15000 rpm)
Safety factor 1.25
Effective band stress, installed 206,000 psi
Interference at installation: 0.080 in. (required for initial pre-stress)

With a retainment band of 0.040”thick and an additional mechanical gap of 0.020” per side the magnetic design is based upon a magnetic air gap of 0.060” over an 8.00” diameter rotor.

3.2. Rotor Length Selection

The following is a summary chart of the airgap shear stress (Torque/rotor radius/ rotor swept area at airgap) used by the standard surface magnet machines produced by Fisher for the past 10 years for forced air-cooled machines. (Increases with diameter)

Model Number	Rotor Diam.	Torque per Axial length (100 C rise)	Gap Shear Stress PSI
M2.5	2.5 in	2 lb-ft	2.44
M3	3.0 in	3 lb-ft	2.55
M5	5.0 in	9 lb-ft	2.75
M7	7.0 in.	21 lb-ft	3.27
M10	10.0 in	52 lb-ft	3.97

From above we selected a rotor O.D. of 8.00”, a starting shear stress is interpolated from the above data needed to select the rotor and stator length. (8” rotor results in a projected shear stress of 3.5 psi which is reasonable for 250 deg F liquid cooling as about equal to the highly forced air cooled machines from Fisher).

Projected torque per axial inch is 29.3 Lb-ft

Required torque is 469.5 Lb-ft (1000 KW at 15000 RPM)

Required active rotor length is 16.0 inches

3.3 Allowable losses

All machines exhibit a certain surface area for the heat to conduct into the liquid cooling jacket or to a finned air cooled jacket. The following chart summarizes some important data taken from the existing machines designed, built and tested by Fisher such as the stator surface loss density. We assume the coil to frame thermal resistance to be 50% of the total thermal resistance of the machine. (deg C/ kW)

Mode	Gap Diam	Stator OD	Stator sq-in/in	Rtheta C/kW Coil-frame	Est W/inAxial	Watts Per in^2
M5	5.0”	6.5	20.4	35	224	10.9
M7	7.0 “	8.45	26.5	26	387	14.6
M10	10.0”	12.16	38.2	9	428	11.2

Average loss density at surface of stator lamination OD is 12.2 W/in^2

Calculate allowable coil temperature:
Required life: 200 hrs at full load.
Assume short life of materials is OK—180 C materials at 180 C = 20 years = 175kHrs
Life is shortened by running above continuous life temps:

Temp	Life
180	175.2k
190	87.6k
200	43.8k
210	21.9k
220	10.9k
230	5.5k
240	2.7k

Therefore, design for 240 C operation with 180 C materials.
Therefore, allowable temp rise of stator cooled with 250F (121C) coolant is 120C

Based on Fisher experience:
Using 12W/in^2 for 60 C rise
24 W/in^2 for 120 C rise of same machine is projected
For an 8-pole machine, with about 3X slot area and 3X back iron compared to Fisher 24-pole designs, but with thermal encapsulation, project 0.75 effectiveness or 18W/in^2.

Allowing for 1.5 inches radially for coolant jacket, from 15 in. allowable OD, leaves 13.5 in. OD at stator lams.

OD swept area for the air gap is 13.5 x 3.1414 x 16 = 678.6 in sq.

Allowable loss would then be 12,204 Watts which implies 98.8% efficiency goal

3.4: Projected Stator Phase Resistance

Begin with a 50/50 losses between total Copper and Iron.
Therefore allowable copper losses would be 6102 Watts.
Assume 3-phase machine
Therefore loss per phase would be 2034 Watts

For coil temp of 240 C, the increase in resistance above 25 C ambient is 1.83
Therefore, the equivalent loss at 25 C would be1112 Watts/phase

Calculate phase current:
DC Current: For 1000 MW at 200 Vdc requires 5000 Adc.
Assuming, for FWBR, Iac/Idc = 0.78,
AC Current: Iac = 3900 Amps/phase

Assume 8 parallel circuits for winding, the per circuit current is 488 Amps (ac), and per circuit copper loss would be 139 Watts.

Conclusion: required resistance, per parallel circuit is 0.58 mOhms (25C)

3.5 Required Turns per Coil

First voltage drop assumption is 25% drop due to series impedance full load
Then required BEMF at 240C is 265 0-peak, L-L, per pole, or 17.7 Vpk, L-L/krpm.
Then required BEMF at 240C is 153 0-peak, L-N, per pole (fundamental).

Calculate pole area: for 16 inch stack, 8 pole,
Apole = 50.3 in^2 = 0.0324 m^2

Assume: Bpk gap = 0.75T at 240 C (= 0.80T at 20 C)

Then Epk, L-N, per turn is: 153.0 Volts

This can be achieved by winding each coil with 1 turn with a
16 inch long stack (for 8 poles)

3.6 Flux per pole calculation

Rgap = 4.0 inches
Lgap = 16 inches
Bgap = 0.75 T
Poles = 8
Phi gap/pole = 24.3 mWb

3.7 Slot area

Length of coils:

Assume: Mean Length of end turns is at 1.5 inches larger than ID of 8 inches. At this radius, the pole pitch is 3.73 inches. Allow 0.5 inches for coil exit at the stack and take the end turn length to be:

Let = 0.5 + 3.73 + 0.5 = 4.73 inches

Then ½ the coils will have total length of:
2 x Stack + 2 x Let = 41.5 inches

and ½ will be:
2 x Stack + 1 x Let = 36.7 inches

Average length per turn is 39.1 inches.

To get 0.58 mOhms at 25 C, need Acu of 0.043 in^2, or diam = 0.2338 inch (54,662 cm = 54 strands of #20 AWG)

With two coil sides per slot, Cu area will be 0.086 in^2.
With heavy film, Wire area will be 0.104 in^2
With 0.45 mechanical fill factor, coil Slot area needs to be 0.231 in^2

Also, slot pitch at stator ID, for 3 slots per pole, is 1.047 inches, which means if slot and tooth are the same area, each is about 0.523"wide at the stator ID.

Slot area needs to be at least 0.231 sq inches min.

3.8 Stator Core Volume

Assume (from above) allowable core loss is 6102 Watts

Loss can be approximated by
Pfe = kfe* f^m * B^n *Volume

B in teeth is different than B in back iron, so total loss is:
Ptot = Pfe_teeth + Pfe_backiron

Frequency is the same, so B and volume of teeth and back iron are 4 variables we can use to apportion losses. Also the material itself is an available choice. The following analysis can be done parametrically, but it's faster to just calculate by trial and error.

Assume tooth/slot area percentage ratio is between 25/75 – 75/25. For Slot area of 0.231 in^2, calculate tooth areas (axial section), with the slot pitch constrained to 0.523 inches at the stator ID.

The required slot depth, ds, to achieve the necessary slot area for Nsp slots per P poles is the solution of the following quadratic equation:

ds^2 + (2 Rid) ds – (Nsp P As)/(pi Ks) = 0

where: ds = slot depth
Rid = stator inner radius
Nsp = Number os slots per pole
P = numper of poles
As = required slot area
Ks = Fraction that slot area is of total slot pitch area (=As+At)

Tooth/Slot Ratio	dslot	Width Slot top	Width Tooth top	Width Slot bottom	Width Tooth bottom
25/75	0.284	0.785	0.262	0.841	0.280
33/67	0.317	0.702	0.346	0.757	0.373
40/60	0.352	0.628	0.419	0.684	0.456
45/55	0.383	0.576	0.471	0.631	0.516
50/50	0.419	0.524	0.524	0.578	0.578
55/45	0.463	0.471	0.576	0.526	0.643
60/40	0.518	0.419	0.628	0.473	0.710
67/33	0.620	0.346	0.702	0.399	0.810
75/25	0.802	0.262	0.785	0.314	0.943

Note: Teeth could be tapered for trapezoidal teeth and slots. (All examples modeled in PC-BDC teeth are based on parallel-sided teeth)

Considering there are about 2.75 inches radially available for teeth plus back-iron, it looks like there is room for larger (deeper) slots, more iron and lower overall losses. The other alternative is to reduce the stator O.D. which would reduce weight substantially.

Given the tooth width, the no-load flux density in the teeth can be estimated. The flux per pole is given by:

Phi_pole = 24.3 mWb, and flux per tooth is 8.10 mWb

Tooth volume summary:

Tooth/Slot	**Tooth Top Width**	**Tooth gap Area in^2**	**Btooth**	**Vol Tooth In^3**	**Vol Teeth total**
25/75	0.262	4.02	3.59	4.16	99.9
33/67	0.346	5.31	2.72	5.52	132.4
40/60	0.419	6.43	2.24	6.72	161.2
45/55	0.576	7.238	1.99	7.585	182.0
50/50	0.524	8.042	1.80	8.464	203.1
55/45	0.471	8.847	1.63	9.359	224.6
60/40	0.628	9.65	1.50	10.28	246.6
67/33	0.702	10.78	1.34	11.61	278.7
75/25	0.785	12.06	1.20	13.27	318.6

Back Iron volume calculations:
Assume: Flux density in back iron is the same as in teeth, although it can be independently controlled
Note: Max OR_bi is about 6.75 inches

Bback iron	Abi (m2)	Abi (in^2)	d_bi (in)	IR_bi (in)	OR_bi (in)	Vol_bi (in^3)
3.59	1.02E-02	15.7	1.02	4.28	5.31	474.2
2.72	1.34E-02	20.8	1.35	4.32	5.67	651.6
2.24	1.62E-02	25.2	1.64	4.35	5.99	818.1
1.99	1.83E-02	28.3	1.84	4.3828	6.23	944.0
1.80	2.03E-02	31.5	2.05	4.4192	6.47	1076.4
1.63	2.23E-02	34.6	2.25	4.4634	**6.72**	1215.9
1.50	2.44E-02	37.8	2.46	4.52	6.98	1363.7
1.34	2.72E-02	42.2	2.75	4.62	7.37	1588.0
1.20	3.05E-02	47.2	3.07	4.80	7.88	1880.1

3.9 Core Losses calculations:

Material choices:

Inputs: f = 1000 Hz
B_teeth = 1.63
B_ backiron = 1.63 (same as Btth)

$P1 = K * f^{m} * B^{n}$ W/kg

$P2 = Kh * f^{1} * B^{a+bB} + Ke * f^{2} * B^{2}$ (Steinmetz)

Material	K (W/kg)		m for f exp (a)	n for B exp	Material density kg/cm^3
Cogent M3 0.009" thk	0.0007563		1.693	2.060	0.00765
	Kh	**Ke**	**a, b for Bh**	**for Be**	
Hiperco 50 6 mil	0.023149	7.2753e-7	1.7, 0	2.00	0.00811
Arnon7 M15) 7mil	0.020589	2.3986e-6	2.977, 0	2.00	0.00745
Metglas				2.00	
M19 29Ga (14 mil)	0.0.01874	3.2187e-6	a=1.308, b=0.356 at = 2.105 abi=1.838	2.00	0.00745

	Loss Density In Teeth W/kg	Teeth Core Loss Watts	Loss Density In Backiron W/kg	BkIron Core Loss Watts	Total Core Loss Watts
Cogent M3 (9 mil) ***	248.84	5029	248.84	30550	35579
Hiperco 50 (6 mil)	55.17	1182	55.17	7180	8362
Arnon (7mil)	55.84	1200	55.84	7267	8463
M19 29Ga (14 mil) ***	94.89	1868	94.89	11345	13212

*** = doubtful calculation, don't have Steinmetz coefficients

Check against allowable losses: Allowable core loss is 6102 Watts. Hiperco is the highest density magnet material available and one of the lowest in core loss.

Selection of Hiperco 50, 6 mil thick:

Note: loss is higher than expected allowance of 6102 Watts. With the core being in direct contact with the cooling jacket, it is conceivable that this will be acceptable. A thorough thermal model is necessary to investigate this more closely. Also, it appears there may be room to use extra iron to lower flux densities and losses.

The selection of 55/45 ratio of tooth to slot seems to be a good starting point:

Dslot = 0.4634
Width_slottop = 0.471
Width_toothtop = 0.576 (not incl tooth tip)
Width_slotbottom = 0.526
Width_toothbottom = 0.643
IR backiron = 4.4634
OR of back iron = 6.72

Wgt Bi = 108.7 kg = 239 lbs
Wgt tth = 21.4 = 47.1 lbs
Wgt total = 130.15 kg = 286.8 lbs

3.10 Demagnetization

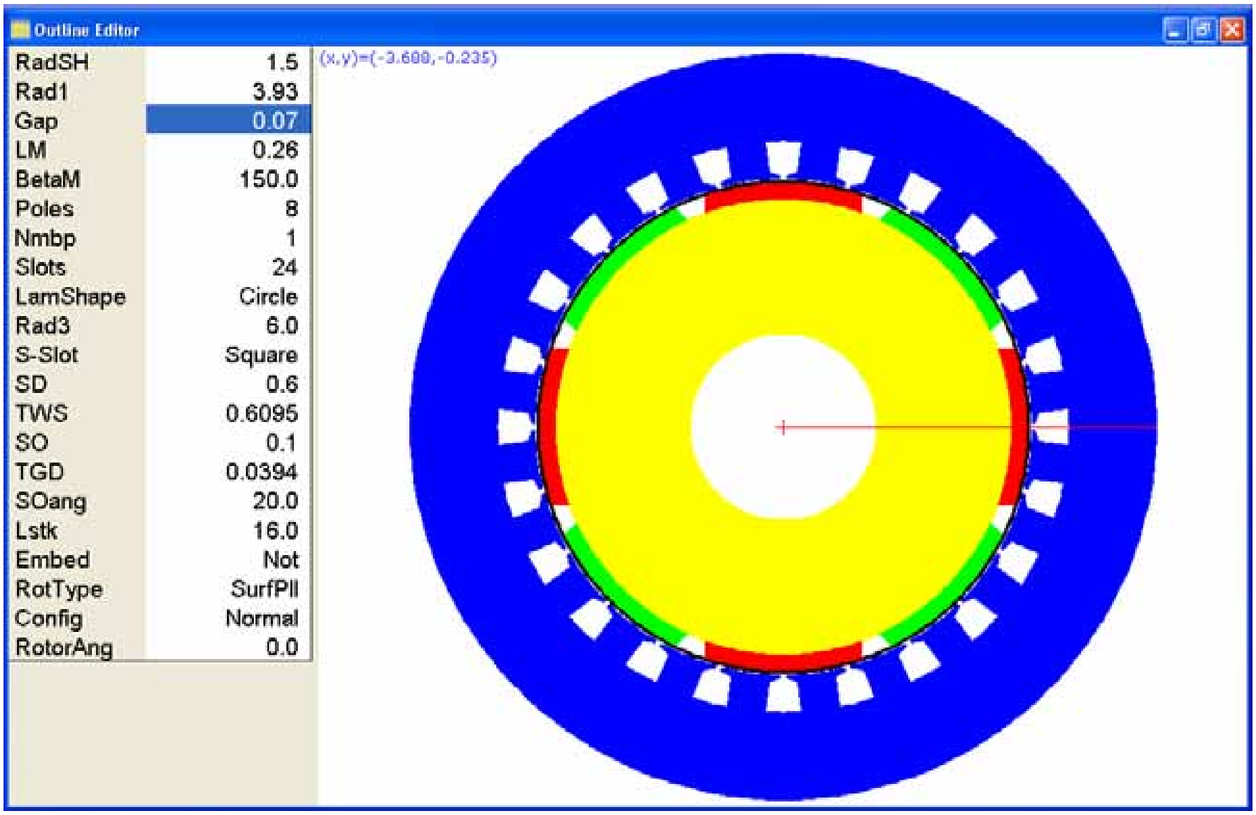
Inputs: Turns/pole: 1
Amps/pole: 488 rms, (apprx 690 peak)
Air-gap: 0.060 inches
Magnet thickness: 0.25 inches
Mag temp: 250C
H_arm(pk) = 175 kA/m (about 2.2 kOe) Taken from vender B-H curve
Approx PC = 0.25/0.06 = 4.2 (PC-BDC shows 3.8)

Using Sm2Co17 (Arnold S3/245), there should be no problem with demagnetization at this current and temperature. PC-BDC model uses Shin-Etsu R33H Samarium.

4.0 Simulation Results Using PC-BDC (SPEED Software)

Using PC-BDC this design was refined and it was determined that the slots should be much deeper to reduce the copper losses at the expense of core iron losses.

4.1 Cross Section Per Sizing From Section 3.0



The final lamination O.D. was reduced from the projected of 13.50” to 12.00” diameter.

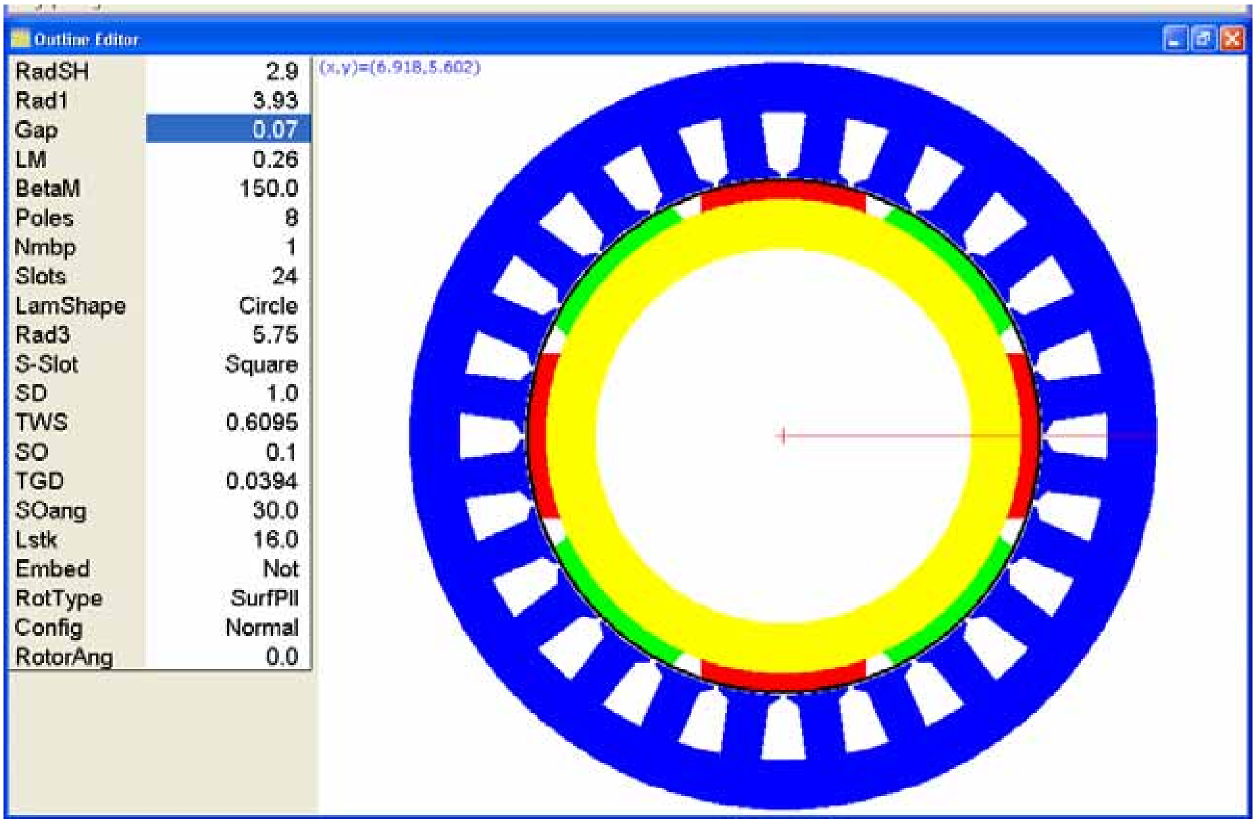
1.013 MW Output @ 15,000 rpm, 205 VDC rectified

Total Losses = 10807 W, Efficiency = 98.95%

Copper Losses = 5416 W Iron Losses = 4885 W Rotor Losses = 505 W

The cross section shown is based on copper losses and iron losses that are close to equal based upon the original assumptions used to size the unit. Since the heating due to copper losses is much more difficult to remove via liquid cooling that iron losses, the copper can be reduced as the iron losses increases. This assumes the O.D. and stack of the machine are retained. After several iterations it was found that when the slot depth is increased to provide more winding space for larger wire cross section, the copper losses are reduced faster than the iron losses are increased. The cross section of the back iron decreases as the slot depth is increased which increased the flux density and iron losses in the stator yoke. The next cross section shows the results of more winding space using deeper slots and less back iron or yoke thickness.

4.2 Revised Cross Section for Higher Iron Losses & Lower Copper Losses



The stator lamination O.D. was further reduced from12.00 to 11.00” diameter.

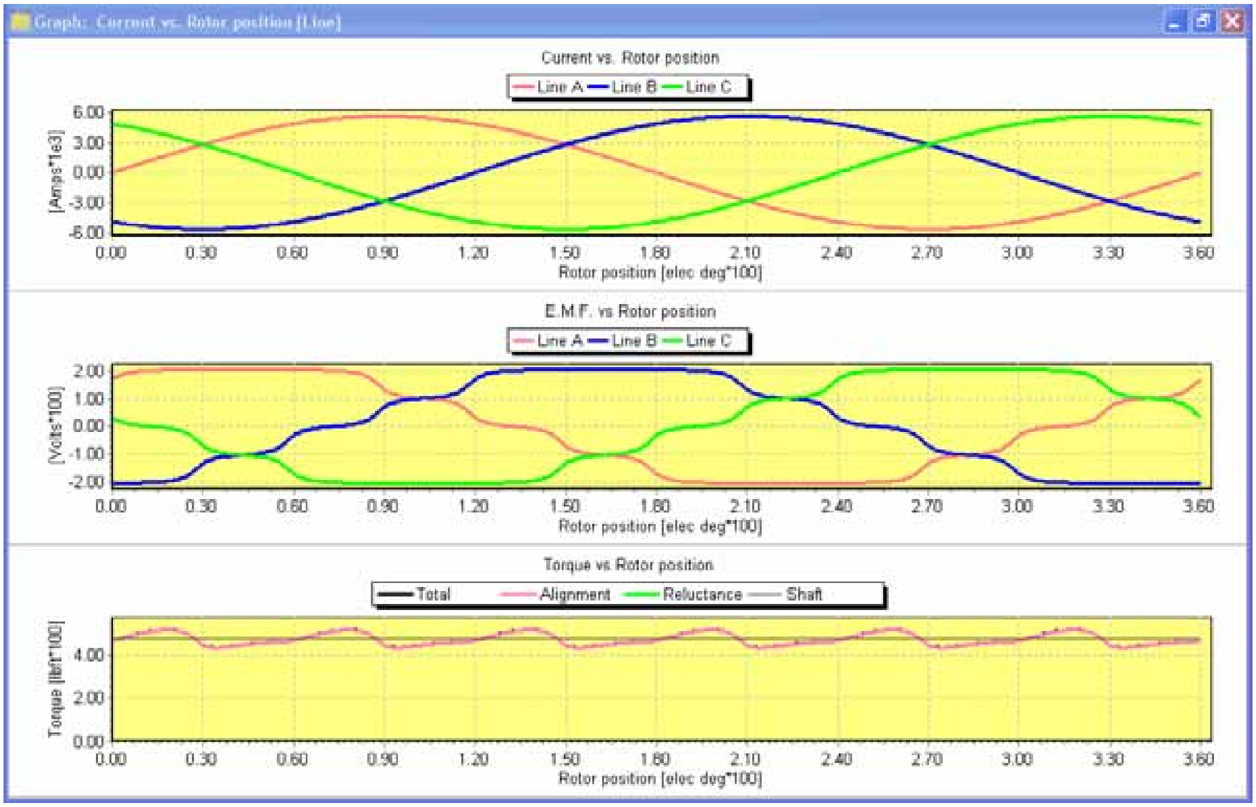
1.003 MW Output @ 15,000 rpm,   205 VDC rectified

Total Losses = 9635 W,   Efficiency = 90.04%

Copper Losses = 2826 W   Iron Losses = 6304 W   Rotor Losses = 505 W

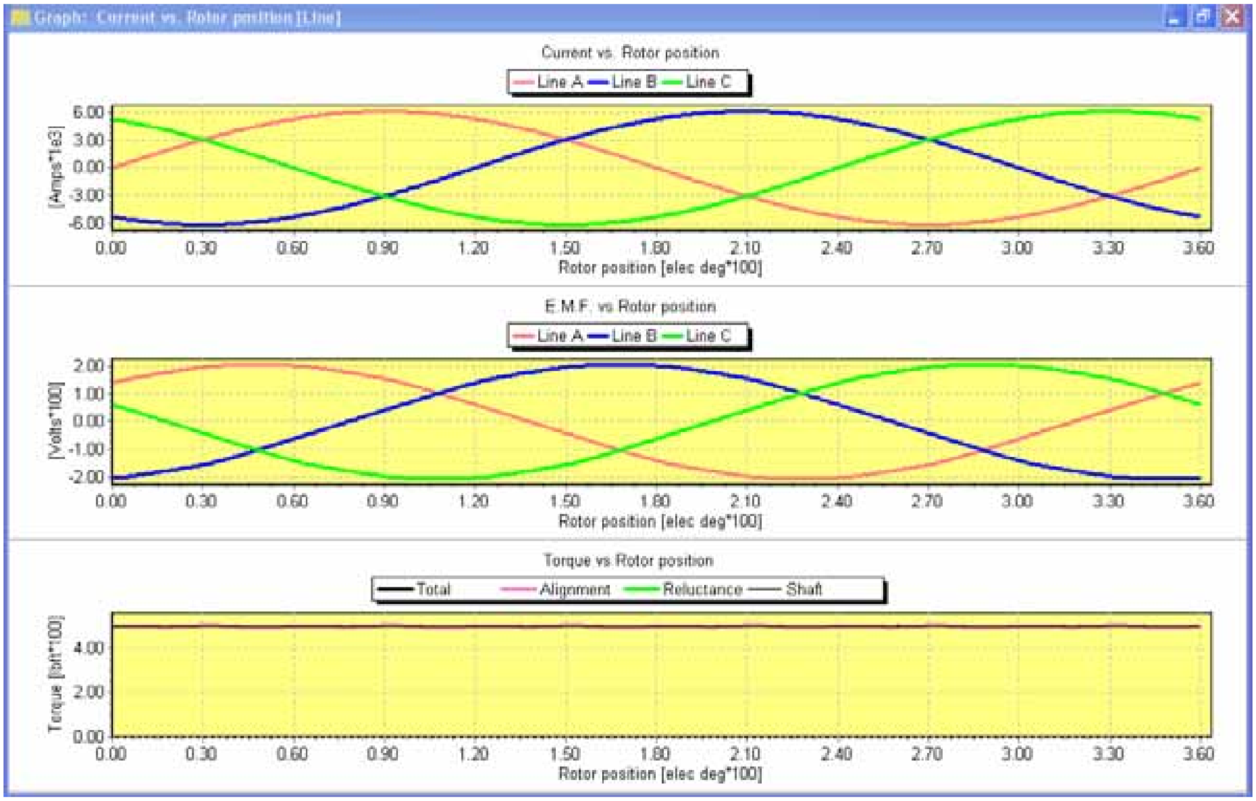
The efficiency has increased slightly and the copper losses are reduced substantially with a less correspondingly increase in iron losses. The extra heat generated from the iron losses is easily extracted due to the lamination contact with the cooling jacket.

4.2.1 Simulated Output Curves @ 15,000 RPM



A sinusoidal shaped voltage wave shape is most desirable from line to line. The middle graph above indicates that an improvement is required. However with the current slot to pole combination, the resulting flux linkage yields the optimum power density. The wave shape can be improved a number of ways but each will reduce the power density slightly. The next example shows those results using the exact same machine dimensions but with magnet overhang and a full stator slot skew to cause the back emf to be sinusoidal.

4.2.2 Simulation Results Using A One Slot Stator Skew



The skewing of either the stator or the rotor magnets equal to the angle between two adjacent stator slots (360 deg/24 slots = 15 deg skew) results in a very nearly perfect sine wave back EMF which results in near zero torque ripple seen by the turbine during generating. The control angle between the output voltage and the back EMF must be increased slightly from 22.5 deg to 25 deg in order to achieve the 1 MW output. This results in a drop in efficiency and higher copper losses, which seems to be still OK. (The stator skewing also reduced the output voltage so some magnet overhang to the stator length was added to increase the flux to compensate for that lost by the skewing.)

1.016 MW Output @ 15,000 rpm, 200 VDC rectified

Total Losses = 10157 W, Efficiency = 99%

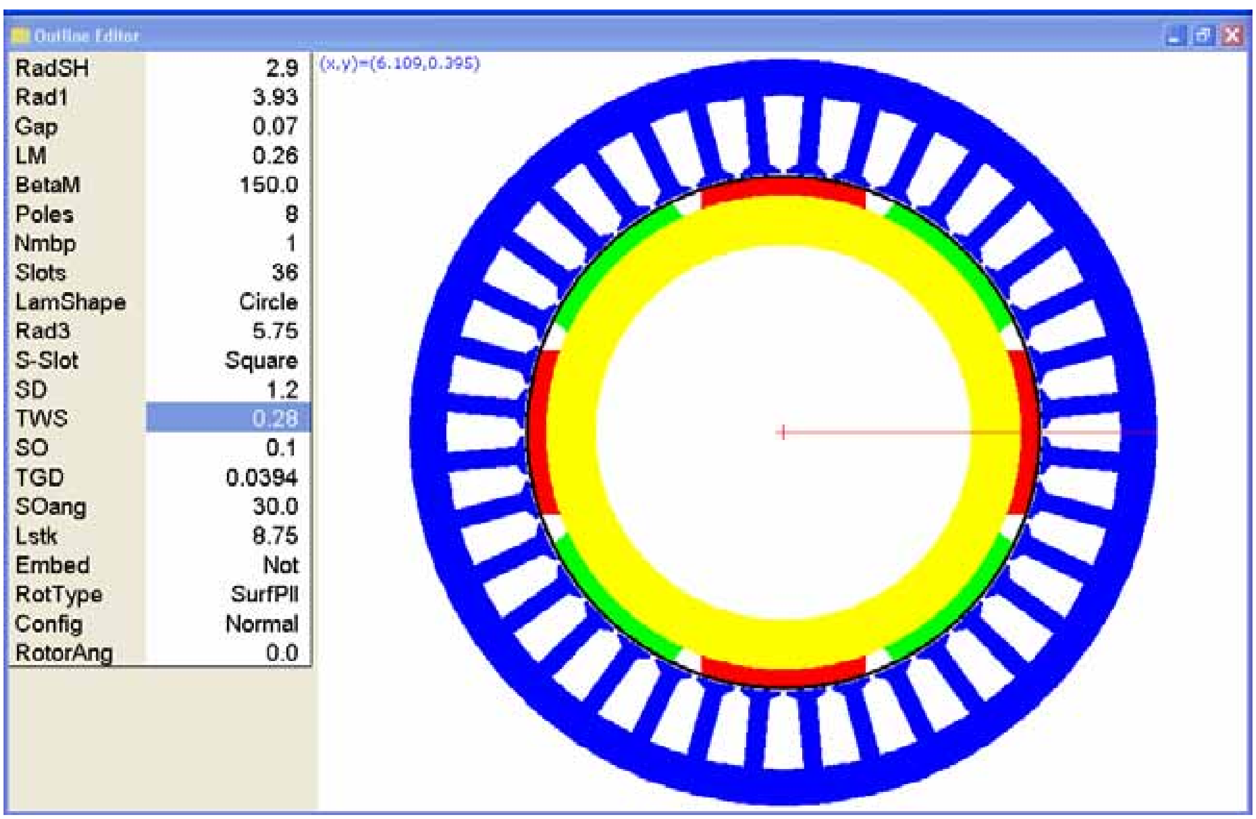
Copper Losses = 3063 W Iron Losses = 6565 W Rotor Losses = 530 W

4.3 High Power Density Generator design.

One more design consideration is presented for a very high density PM generator with the same 12.00” stator O.D. & 13.50” frame/cooling jacket O.D. The 8-pole rotor over the magnets is the same as the previous designs at 8.00” O.D. The main difference is the stack length is shortened from 16” to 8.75” The number of stator slots was increased in accordance with the new stack length to achieve the same output voltage at 15,000 rpm under full load of 1 MW. Since the coils cannot be wound with less than a single turn per coil the 8 parallel paths then had to be changed to 4 through the phase windings to achieve the correct number of effective turns to go with the reduced magnet flux required to generate the rectified 200 VDC min. Both the current density (amps/cross section of copper per turn) and the stator lamination flux density are higher than the other designs. Since the rotor is much shorter than the other designs the gap shear stress increased from 3.6/3.7 psi to 6.8 psi.

Neither Fisher nor Motorsoft have ever attempted such a high a power density machine but many other designs are as high as 10 psi. However this 6.8 value is certainly achievable as long as the cooling system can remove the heat from the windings and the laminations. A more detailed design simulation analysis would be required using a good thermal FEA package. From such an analysis the needed flow of cooling oil could be determined to facilitate cooling to prevent the windings from ever exceeding their design temperature.

4.3.1 Cross Section of High Density 8 Pole – 36 Slot Machine With a 8.75” Stack

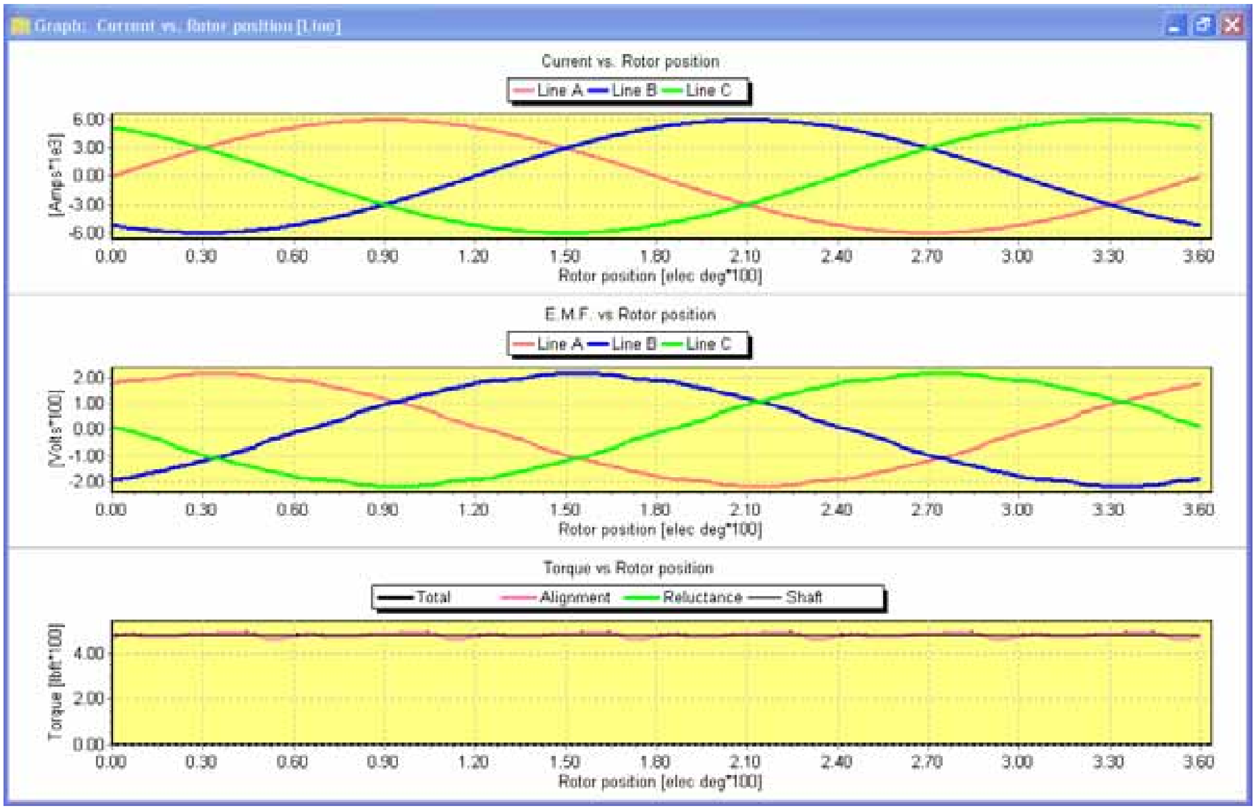


1.011 MW Output @ 15,000 rpm,   207 VDC rectified

Total Losses = 9921 W, Efficiency = 99%

Copper Losses = 4910 W Iron Losses = 4683 W Rotor Losses = 328 W

4.3.2 Simulated Output Curves @ 15,000 RPM



The back emf is quite sinusoidal which produces very little torque ripple to drive the generator.

5.0 Summary

The original calculations in section 3 were used to size the unit based upon the spec dimensions, the required performance, the maximum rotor diameter for 15,000 rpm and safe thermal assumptions based upon experience. The first motor modeled in section 4.1 was intended to be based upon the sizing. However it soon became apparent that for the stator/rotor lengths and rotor diameter selected the stator O.D. could be reduced from the maximum of 13.50'' to 12.00". Even then the results indicated that the yoke was too thick with the copper and iron losses about equal.

Section 4.2 shows the results of a smaller stator (11.50" O.D.) and higher core losses but much lower copper losses. The cross section even looks more reasonable. Both models, the original and this one with the 24 slot stator and 8 poles, exhibited a sort of line to line trapezoid back emf which would cause significant torque which might make the turbine unhappy. So we simply skewed the stator stack from one end to the other a single slot. The result is very low torque ripple and a very nice sine back emf as shown in 4.2.2.

Even with these results it was suspected that if a higher density could be properly cooled a shorter unit might be feasible. Therefore continued simulations were tried until the results shown in section 4.3.1 resulted. The number of slots was increased from 24 to 36 and the stack was reduced from 16" down to 8.75". The skew was removed as it is not required with this slot to pole configuration. The result is just as an efficient machine as the others in a much smaller package. The power density is almost doubled with about the same losses. The amount of heat to be removed is the same as the others but the surface area of the stator core that is in contact with the cooling jacket is less than the longer stack. However, is believed that this design is feasible to do this job.

SECTION NUMBER	PC-BDC FILE	POLES SLOTS	EFFICIENCY (%)	TOTAL LOSSES	ACTIVE WEIGHT
4.1	FLA240C.bd4	8P-14S	98.95	10808 W	430 lbs
4.2	FLA240CJIM24.bd4	8P-24S	99.05	9635 W	298 lbs
4.2	FLA240jim24SKEWED.BD4	8P-24S	99.01	10157W	301 lbs
4.3	FLA240CJIM36short.bd4	8P36S	99.05	9711 W	158 lbs

The weights do not include frames, shafts bearings etc. Only the active parts, such as the magnets, rotor yoke, stator lamination stack and copper, are included.

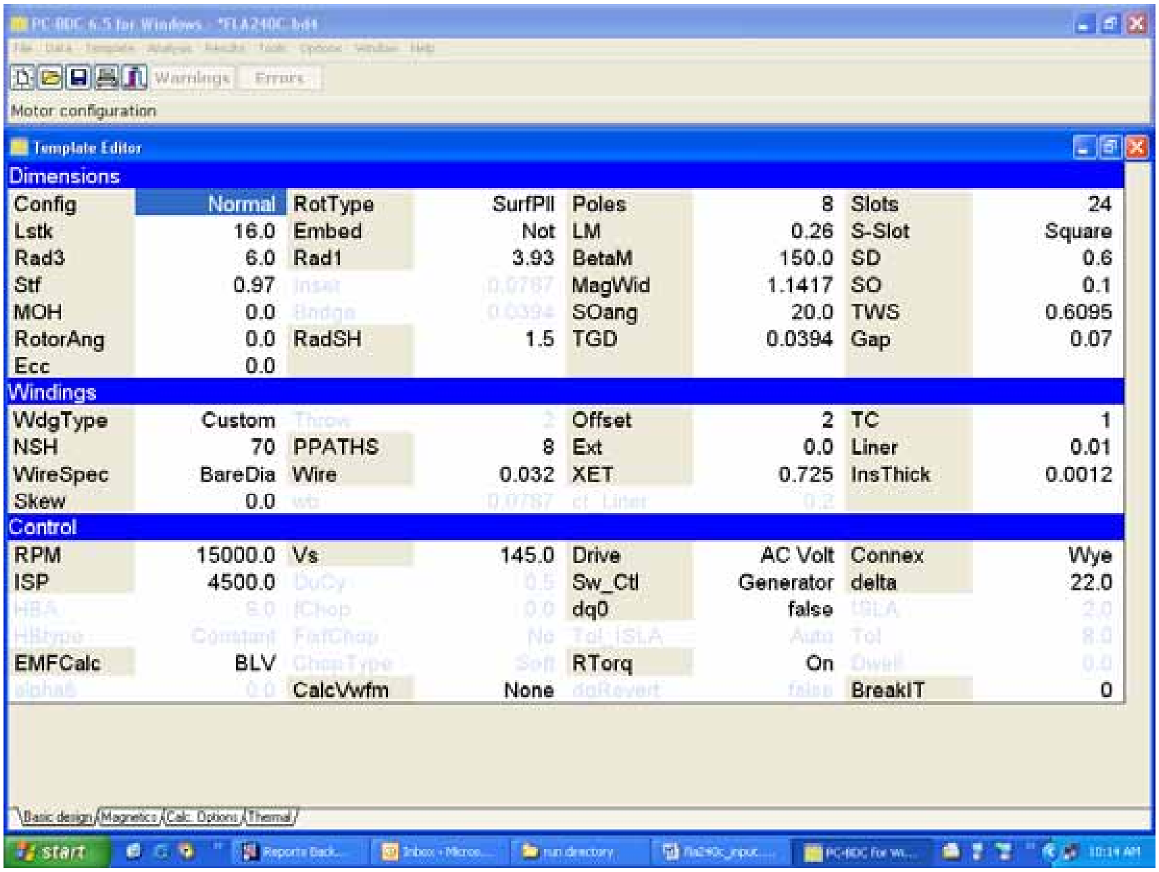
APPENDIX

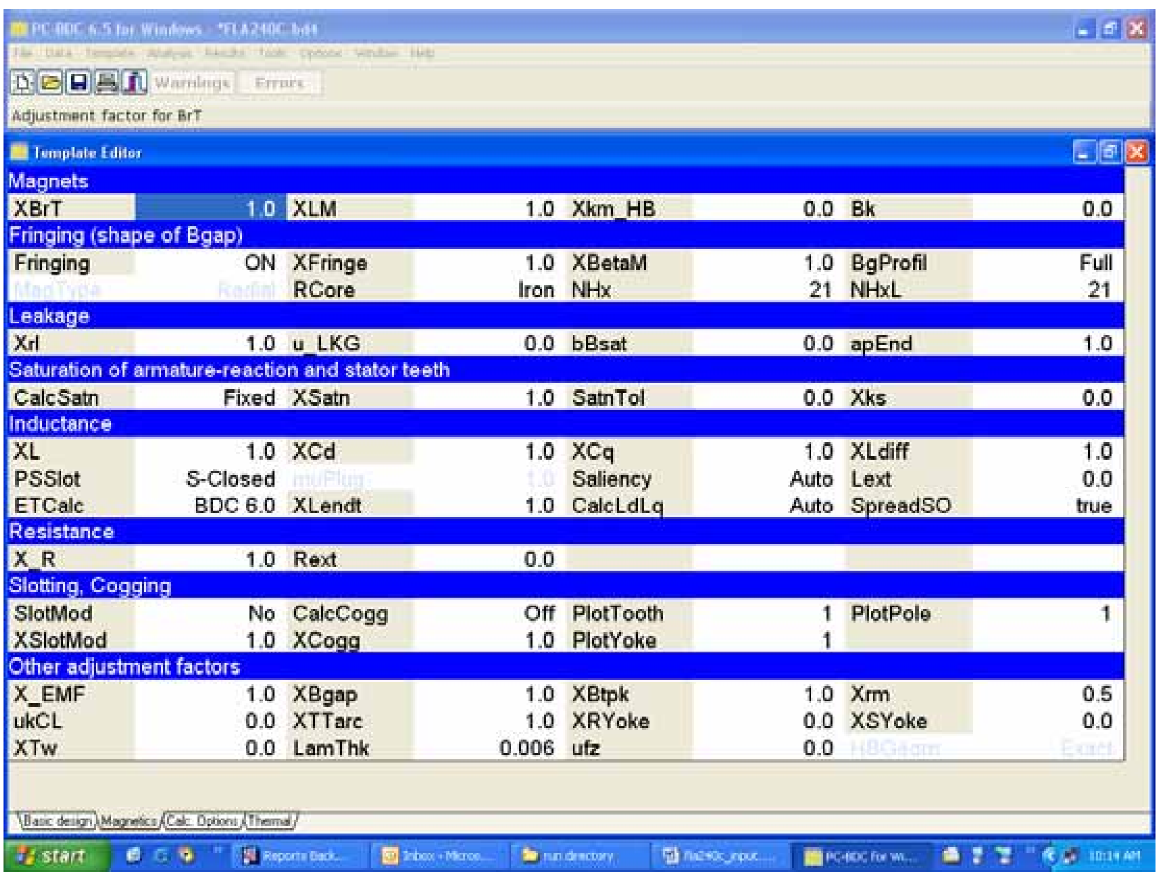
This Appendix contains the input data used to generate the results for each machine design discussed in the main body of the report as well as the Design Sheet for each design. Version 6.5 of PC-BDC for Windows was used for machine design and analysis.

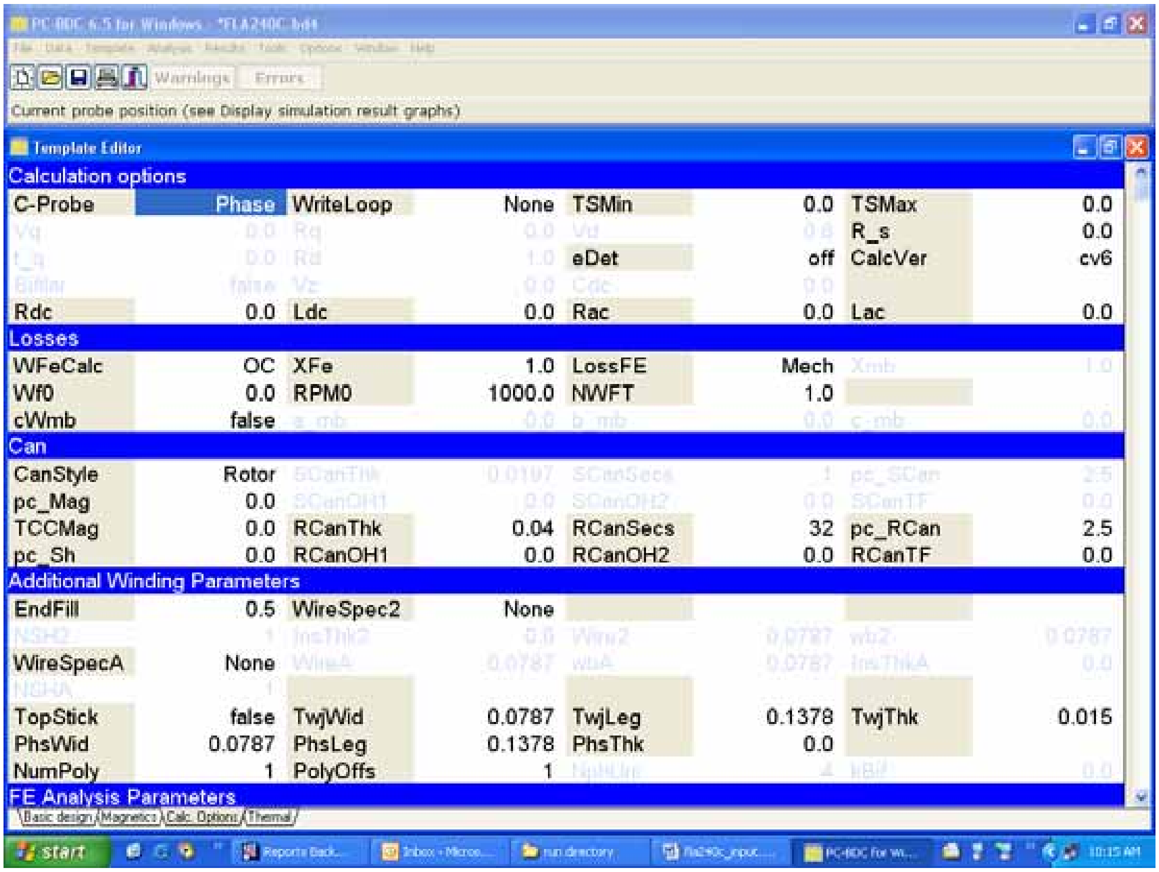
Material selections were made from the database supplied with SPEED for this effort and were the same across all of the designs. “Hiperco50 (7 mil)” was used for the stator, rotor, and shaft steels. “S-L 30MGO” was used for the permanent magnet material.

For each design, in the order presented in the main body, the Template Data input, the winding configuration, and the Design Sheet are shown in this Appendix. The Design Sheet presented for each design was calculated using the Static Analysis calculation in PC-BDC.

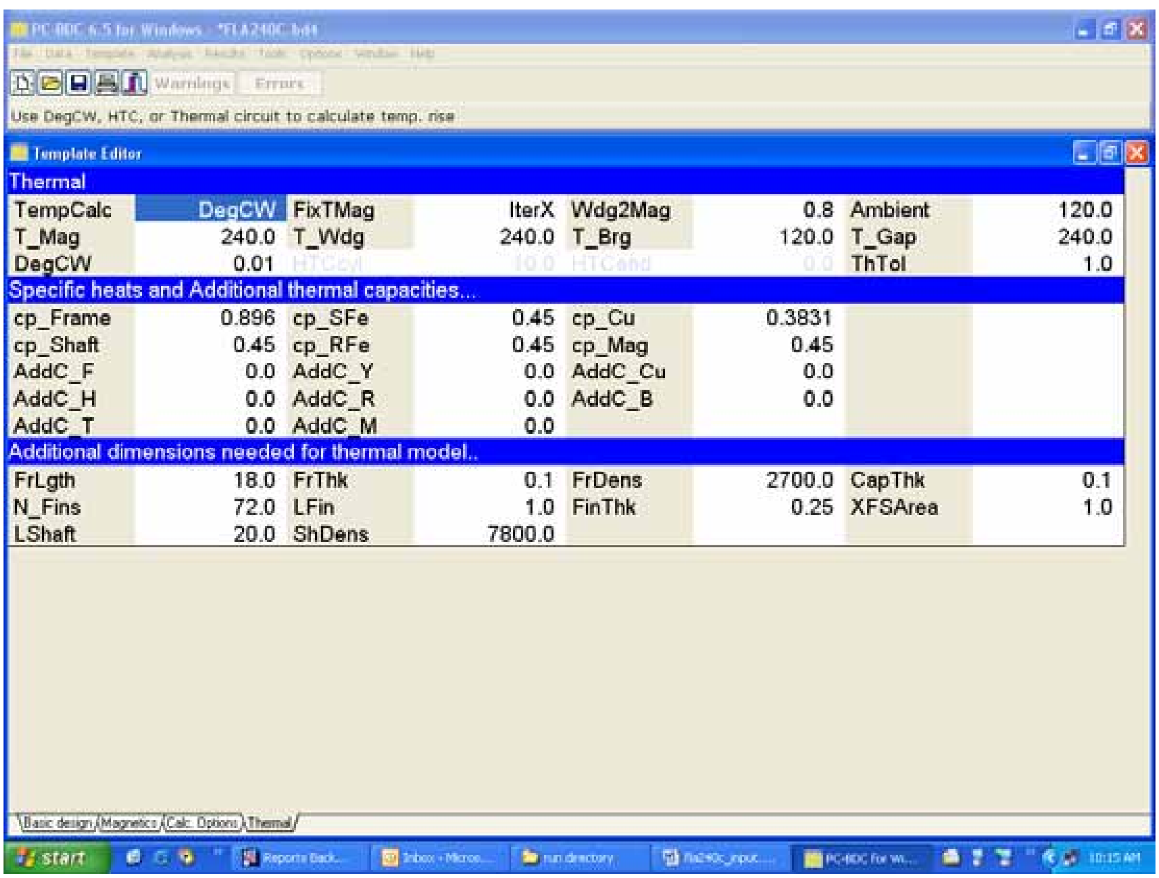
This Appendix was generated by the program monitor from AFRL/PRPG (Charles Kessler), as opposed to the report’s authors, in order to enhance the basic report and further support its conclusions.


PC-BDC 6.5 for Windows - *FLA240C.bd4
Warnings Errors
Motor configuration
Template Editor
Dimensions
Config Normal RotType SurfPll Poles 8 Slots 24
Lstk 16.0 Embed Not LM 0.26 S-Slot Square
Rad3 6.0 Rad1 3.93 BetaM 150.0 SD 0.6
Stf 0.97 MagWid 1.1417 SO 0.1
MOH 0.0 SOang 20.0 TWS 0.6095
RotorAng 0.0 RadSH 1.5 TGD 0.0394 Gap 0.07
Ecc 0.0
Windings
WdgType Custom Offset 2 TC 1
NSH 70 PPATHS 8 Ext 0.0 Liner 0.01
WireSpec BareDia Wire 0.032 XET 0.725 InsThick 0.0012
Skew 0.0
Control
RPM 15000.0 Vs 145.0 Drive AC Volt Connex Wye
ISP 4500.0 Sw_Ctl Generator delta 22.0
dq0 false
EMFCalc BLV RTorq On
CalcVwfm None BreakIT 0
Basic design Magnetics Calc. Options Thermal
start

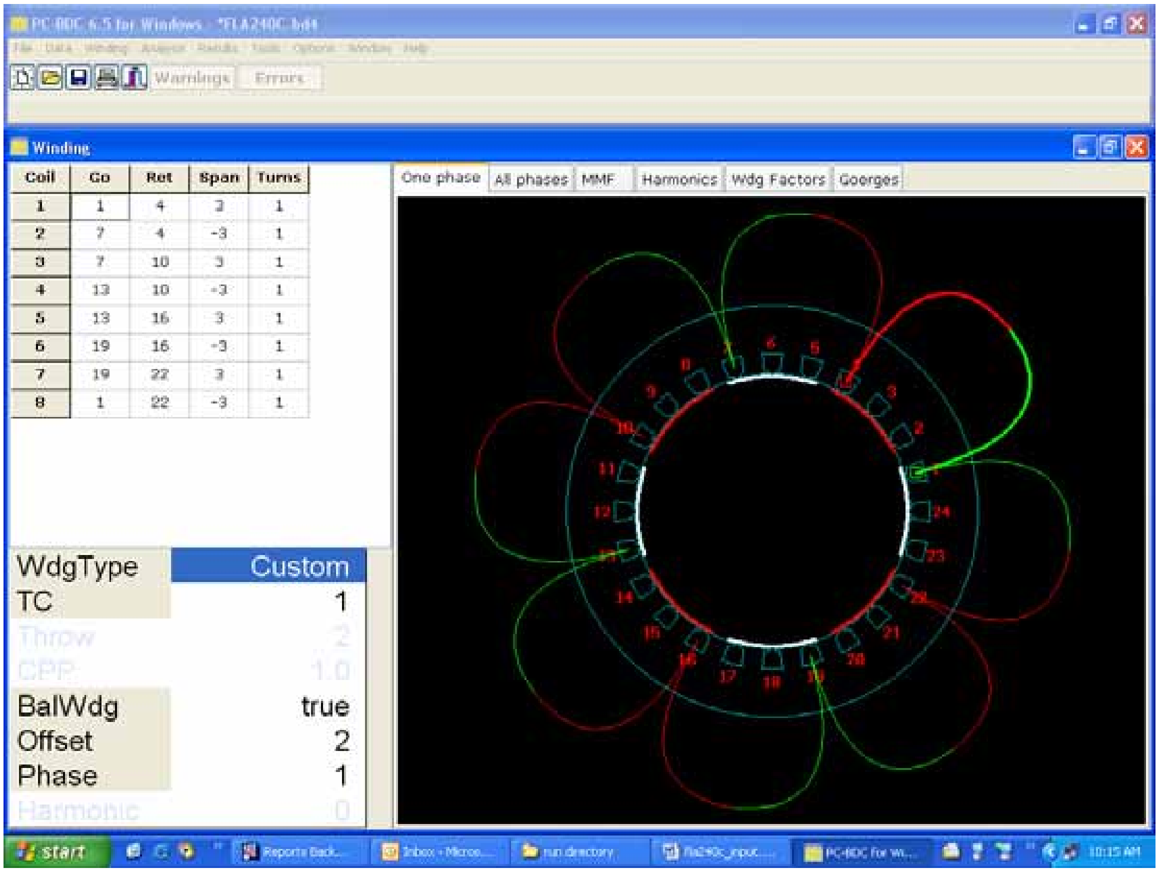

PC-BDC 6.5 for Windows - *FLA240C.bd4
Warnings Errors
Adjustment factor for BrT
Template Editor
Magnets
XBrT 1.0 XLM 1.0 Xkm_HB 0.0 Bk 0.0
Fringing (shape of Bgap)
Fringing ON XFringe 1.0 XBetaM 1.0 BgProfil Full
RCore Iron NHx 21 NHxL 21
Leakage
Xrl 1.0 u_LKG 0.0 bBsat 0.0 apEnd 1.0
Saturation of armature-reaction and stator teeth
CalcSatn Fixed XSatn 1.0 SatnTol 0.0 Xks 0.0
Inductance
XL 1.0 XCd 1.0 XCq 1.0 XLdiff 1.0
PSSlot S-Closed Saliency Auto Lext 0.0
ETCalc BDC 6.0 XLendt 1.0 CalcLdLq Auto SpreadSO true
Resistance
X_R 1.0 Rext 0.0
Slotting, Cogging
SlotMod No CalcCogg Off PlotTooth 1 PlotPole 1
XSlotMod 1.0 XCogg 1.0 PlotYoke 1
Other adjustment factors
X_EMF 1.0 XBgap 1.0 XBtpk 1.0 Xrm 0.5
ukCL 0.0 XTTarc 1.0 XRYoke 0.0 XSYoke 0.0
XTw 0.0 LamThk 0.006 ufz 0.0
Basic design Magnetics Calc. Options Thermal
start



Warnings
Errors
Current probe position (see Display simulation result graphs)
Template Editor
Calculation options
C-Probe Phase WriteLoop None TSMin 0.0 TSMax 0.0
R_s 0.0
eDet off CalcVer cv6
Rdc 0.0 Ldc 0.0 Rac 0.0 Lac 0.0
Losses
WFeCalc OC XFe 1.0 LossFE Mech
Wf0 0.0 RPM0 1000.0 NWFT 1.0
cWmb false
Can
CanStyle Rotor
pc_Mag 0.0
TCCMag 0.0 RCanThk 0.04 RCanSecs 32 pc_RCan 2.5
pc_Sh 0.0 RCanOH1 0.0 RCanOH2 0.0 RCanTF 0.0
Additional Winding Parameters
EndFill 0.5 WireSpec2 None
WireSpecA None
TopStick false TwjWid 0.0787 TwjLeg 0.1378 TwjThk 0.015
PhsWid 0.0787 PhsLeg 0.1378 PhsThk 0.0
NumPoly 1 PolyOffs 1
FE Analysis Parameters
Basic design Magnetics Calc. Options Thermal
start



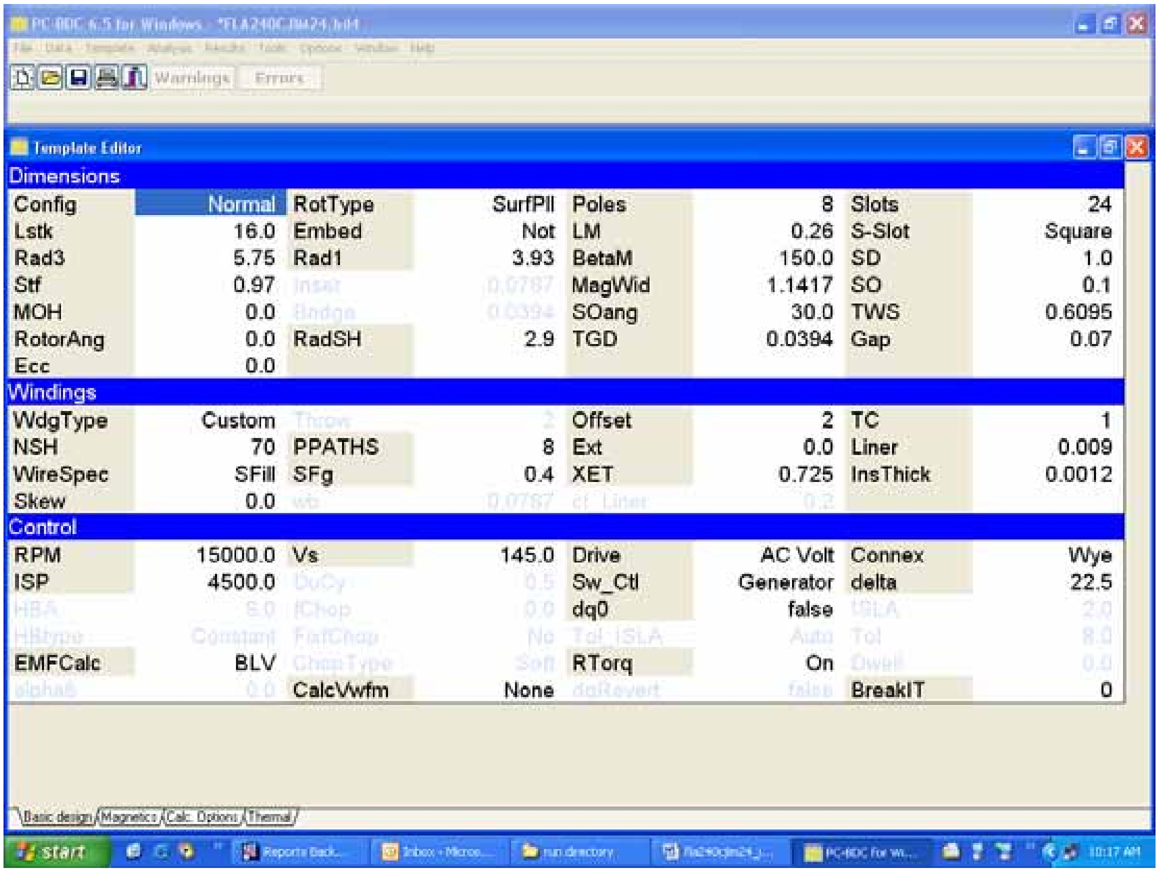
Warnings
Errors
Use DegCW, HTC, or Thermal circuit to calculate temp. rise
Template Editor
Thermal
TempCalc DegCW FixTMag IterX Wdg2Mag 0.8 Ambient 120.0
T_Mag 240.0 T_Wdg 240.0 T_Brg 120.0 T_Gap 240.0
DegCW 0.01 ThTol 1.0
Specific heats and Additional thermal capacities...
cp_Frame 0.896 cp_SFe 0.45 cp_Cu 0.3831
cp_Shaft 0.45 cp_RFe 0.45 cp_Mag 0.45
AddC_F 0.0 AddC_Y 0.0 AddC_Cu 0.0
AddC_H 0.0 AddC_R 0.0 AddC_B 0.0
AddC_T 0.0 AddC_M 0.0
Additional dimensions needed for thermal model..
FrLgth 18.0 FrThk 0.1 FrDens 2700.0 CapThk 0.1
N_Fins 72.0 LFin 1.0 FinThk 0.25 XFSArea 1.0
LShaft 20.0 ShDens 7800.0
Basic design Magnetics Calc. Options Thermal
start

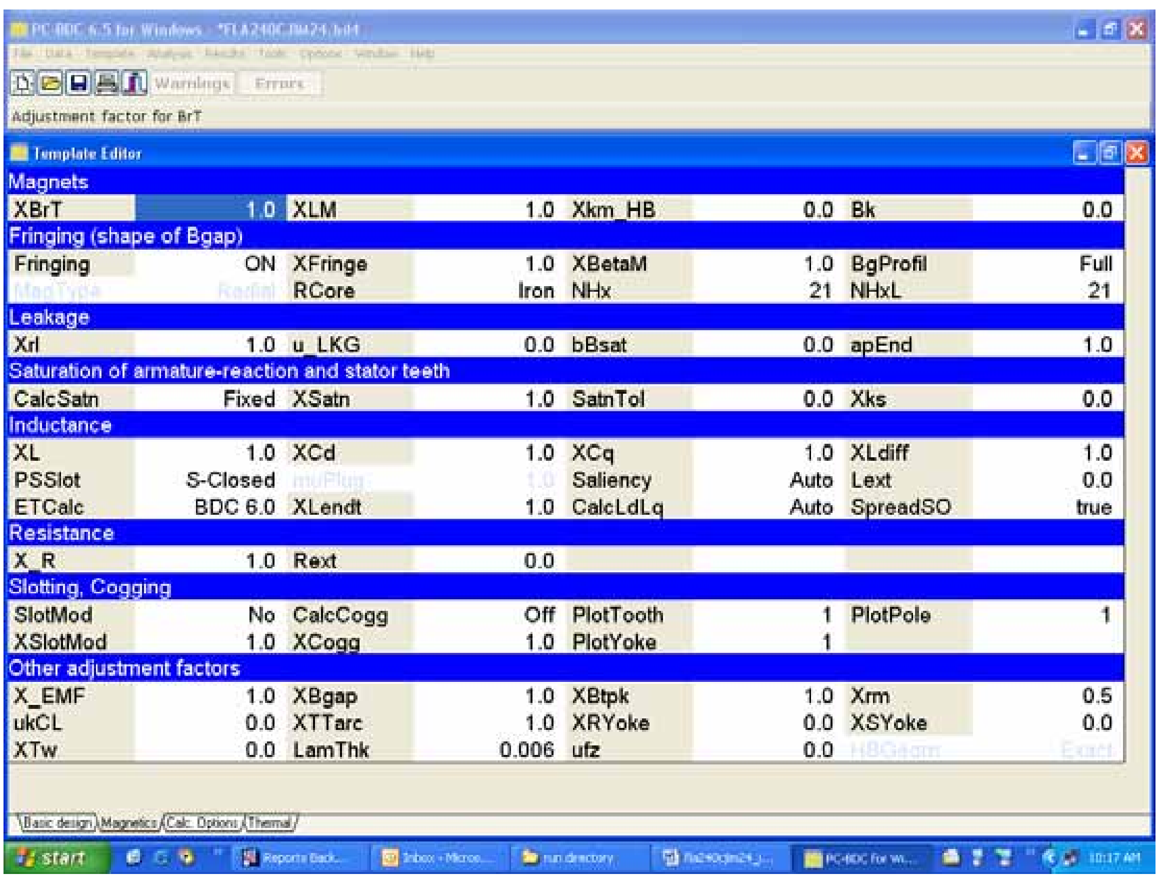

PC-BDC 6.5 for Windows - *FLA240C.bd4
Warnings
Errors
Winding
Coil
Go
Ret
Span
Turns
1 1 4 3 1
2 7 4 -3 1
3 7 10 3 1
4 13 10 -3 1
5 13 16 3 1
6 19 16 -3 1
7 19 22 3 1
8 1 22 -3 1
One phase
All phases
MMF
Harmonics
Wdg Factors
Goerges
WdgType Custom
TC 1
Throw 2
CPP 1.0
BalWdg true
Offset 2
Phase 1
Harmonic 0
start

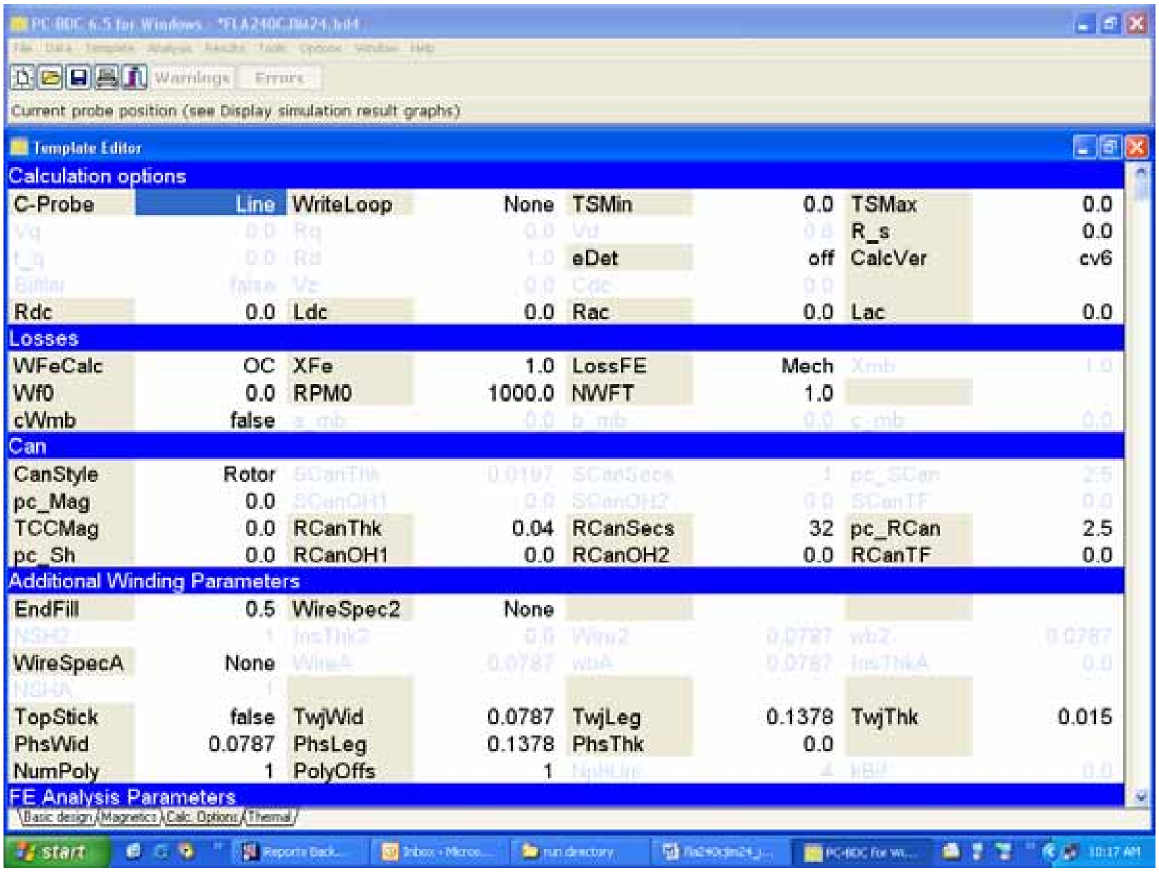
```
PC-BDC 6.5 for Windows (6.5.2.8) 3/8/2005 10:17:01 AM
C:\Documents and Settings\kesslecl\My Documents\Hendershot report\run
directory\FLA240CJIM24.bd4
Wright-Patterson AFB
PC-BDC main title
PC-BDC sub-title

1 Dimensions:--------------------------------------------------------------

RotType     SurfPll          Embed            Not          Poles            8
Stator..
StatorOD     11.500 in       LamShape      Circle          Slots           24
SYoke         0.750 in       ASD            1.000 in       SP           3.000
Rad3          5.750 in       Rad2           5.000 in       S-Slot      Square
TWS           0.610 in       SD             1.000 in       SO           0.100 in
TGD           0.039 in       SOang         30.000 mDeg     Stf          0.970
Rotor..
MOH           0.000 in       Nmbp               1          Skew         0.000
RotorOD       7.860 in       Rad1           3.930 in       Gap          0.070 in
LM            0.260 in       BetaM        150.000 eDeg     pupa         0.833
RYoke         0.770 in                                     RadSH        2.900 in
DHub          7.340 in       wNeck          0.303 in
MEdge         0.276 in       LM_min         0.260 in
wMag          2.527 in
Lstk         16.000 in       Lrotor        16.000 in       Lstator     16.330 in

2 Magnet Data:-------------------------------------------------------------

Magnet    S-L 30MGO
Br            1.140 T        Hc          1100.000 kA/m     MuRec        1.020
CBr          -0.030 %/DegC   CHc           -0.220 %/DegC   DMag      8400.000 kg/m3
BrT           1.065 T        HcT          567.600 kA/m
Nuisance      0.000 in       BrTnu          1.065 T        MuRecnu      1.020

3 Control Data:------------------------------------------------------------

RPM       15000.000 rpm      Vs           145.000 V        Drive      AC Volt
EMFCalc         BLV          delta         22.500 eDeg     Sw_Ctl   Generator

4 Winding Data:------------------------------------------------------------

Connex          Wye
WdgType      Custom
Offset            2          CPP            1.000
Tph           1.000          PPATHS             8          SPP          1.000
Layers        2.000          CSidesPh          16          Z           48.000
MLT          39.473 in       LgthOEnd      18.379 in       Ext          0.000 in
EndFill       0.500          LaxPack       17.396 in       Liner    9.000E-03 in
WireSpec      SFill          SFg            0.400
NSH              70          WireDia        0.044 in       InsThick 1.150E-03 in
SFg           0.400          SFn            0.600          MaxSFn       0.593
Aslot         0.531 in^2     ASlotLL        0.499 in^2     ACond        0.106 in^2
GPAslot       0.535 in^2     ATstick        0.031 in^2     TopStick     false
TwjWid        0.079 in       TwjLeg         0.138 in       TwjThk       0.015 in
PhsWid        0.079 in       PhsLeg         0.138 in       PhsThk       0.000 in
ATwj      5.315E-03 in^2     APhs           0.000 in^2
XET           0.725          ETCalc       BDC 6.0          Rext         0.000 ohm
Nse           1.273          X_R            1.000          Ax1         37.500 mDeg
T_Wdg       240.000 DegC     Rph0       5.881E-05 ohm      R_LL     1.176E-04 ohm
T_c         240.000 DegC     Rph        5.881E-05 ohm/ph   TFRho        1.865
Inductances...
Lph       1.131E-03 mH       Mph           -0.000 mH       XL           1.000
```

```
Lg        6.237E-04 mH      LSlot     3.762E-04 mH      Lendt     1.309E-04 mH
Mg           -0.000 mH      MSlot         0.000 mH      LDiff     1.195E-04 mH
Lsigma    6.266E-04 mH      Msigma    4.423E-05 mH      XLdiff        1.000
Lgg       2.780E-03 mH      Mgg          -0.001 mH      PCSlot        1.473
LL_d      2.681E-03 mH      LL_q      2.674E-03 mH      L_LL      2.678E-03 mH
Lg_0      5.043E-04 mH      Lg_2      1.242E-06 mH      Laa_d     1.132E-03 mH
Ld        1.341E-03 mH      Lq        1.337E-03 mH      Laa_q     1.130E-03 mH
Xd        8.423E-03 ohm/ph  Xq        8.400E-03 ohm/ph  Xsigma    3.659E-03 ohm/ph
XCd           1.000         XCq           1.000         Lext          0.000 mH
Gd            0.216         Gq            0.215         XLendt        1.000
kw1           1.000         Xm0           0.022 ohm/ph
ks1           1.000         kp1           1.000         kd1           1.000
ksg           0.811         fz            1.021         PSSlot     S-Closed
Saliency       Auto         CalcLdLq       Auto         muPlug        1.000
i1_Ang    -2829.896 A       i2_Ang     5659.793 A       i3_Ang    -2829.896 A

5 Magnetic Circuit Design:-----------------------------------------------------

T_Mag       240.000 DegC    T_r         240.000 DegC    XBrT          1.000
BrT           1.065 T       BgOC          0.793 T       Hca         830.695 kA/m
BgAvOC        0.653 T       PhiG         21.004 mWb     BgA/BgOC      0.824
Bg1OC         0.963 T       PhiM1        19.708 mWb     Bg1/BgOC      1.214
BmOC          0.848 T       Bm/BrT        0.796         XBtpk         1.000
HmOC       -169.305 kA/m    Hm/HcT       -0.298         PC            3.985
Bst           1.313 T       Bsy           1.340 T       Bry           1.321 T
XTw           0.000         XSYoke        0.000         XRYoke        0.000
kT            0.118 Nm/A    kE            0.129 Vs/Rad  krpmNL       15.000 krpm
kSat          1.000         XSatn         1.000         CalcSatn      Fixed
Xks           0.000         ks            0.000         XTTarc        1.000
EffWst        0.610 in      EffLst        0.847 in      ukCL          0.000
XBgap         1.000         X_EMF         1.000         k_rpf         1.000
eLLpk       203.002 V       eTmax        96.357 V       Bslot     8.723E-05 T
IBk       21943.644 A       Bk            0.000 T       Hk         -830.695 kA/m
ILR       1.233E+06 A       BmLR        -53.166 T       HmLR      -4.23E+04 kA/m
IC180     2.959E+06 A       BmC180     -128.948 T       HmC180    -1.01E+05 kA/m
BHmag       143.528 kJ/m3   Carter        1.005         Xrm           0.500
Amhp         20.212 in^2    Aghp         20.761 in^2    Rghp      1.062E+05 At/Wb
Pm0           2.531 uWb/At  Xrl           1.000         prl           0.196
apEnd         1.000         Pend          0.000         Lme           0.260 in
u_LKG         0.000         f_Lkg         0.950         if_Lkg        1.053
Fringing         ON         XFringe       1.000         XBetaM        1.000

6 Constant AC Volts static performance [phasor diagram]:-----------------------

OpMode    Generating         Vs          145.000 V       RPM       15000.000 rpm
Tshaft      475.403 lbft    Pshaft    1.012E+06 W       Eff          98.918 %
WCu        2825.787 W       WFe        6304.168 W       WWF           0.000 W
WCan        504.936 W       WMagnet       0.000 W
WTotal     9634.891 W       TempRise    120.000 DegC    Jrms       4711.357 A/in^2
IWpk       5659.793 A       IWav       3603.113 A       IWrms      4002.078 A
ILpk       5659.793 A       ILav       3603.113 A       ILrms      4002.078 A
IDC_P      6907.043 A       WFeCalc          OC         Pelec     1.002E+06 W
Eq1          87.561 V       Vph1         83.716 V       VLL1        145.000 V
Iph1       4002.078 A       Is            0.000 A
Iq1        3822.197 A       Id1        1186.354 A       gammaACV     17.244 deg
Vq1          77.343 V       Vd1          32.037 V       delta        22.500 deg
Bg1Load       0.923 T       phi          -5.256 eDeg    PF            0.996
Bqad          0.000 T       Phida1        1.272 mWb     Phiqa1        4.079 mWb
BmLoad        0.787 T       Bma          -0.061 T       Fda1       -400.535 At/gap
Tgap_PS     471.588 lbft    TEI_PS      471.438         Trel_PS       0.149 lbft
Tgap        472.206 lbft    Tei         472.056 lbft    Trel          0.149 lbft
Tloop       472.197 lbft
```

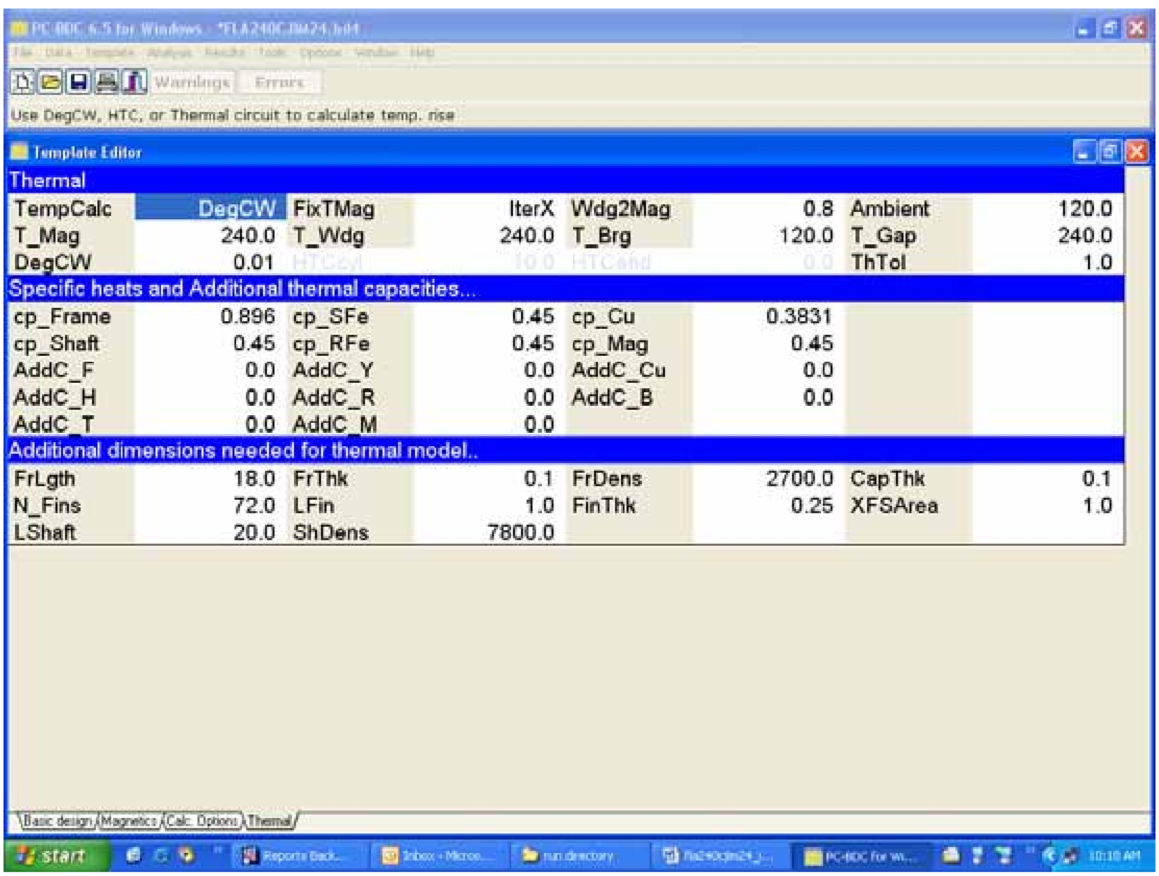
```
Vd0         204.814 V       Pelec     1.002E+06 W

8 Steady-State Thermal Model:-----------------------------------------------

TempCalc      DegCW         FixTMag       IterX         Ambient    120.000 DegC
DegCW      1.000E-02 degC/W HTCcyl       10.000 W/m2/C  HTCend       0.000 W/m2/C
TempRise    120.000 DegC    T_c         240.000 DegC    T_r        240.000 DegC
T_f         240.000 DegC    T_y         240.000 DegC    HeatFlux     0.000 kW/m^2
SlotPeri      2.829 in      Liner     9.000E-03 in      ct_Liner     0.200 W/mC
SSArea       45.264 in^2    C_motor     112.517 kJ/C    ThRSlot  1.631E-03 C/W
FSArea      883.997 in^2

9 Miscellaneous:------------------------------------------------------------

Weights...
wt_Cu        32.307 lb      wt_Fe       239.702 lb      wt_Mag      26.012 lb
wt_Tot      298.021 lb      wt_Shaft    142.800 lb      wt_Frame    39.567 lb
wt_FeS      170.983 lb      wt_FeR       68.719 lb      wt_RSS     238.360 lb
Inertia components...
RotJ          0.506 kg-m2   RotJSS        0.509 kg-m2   RotJSh       0.176 kg-m2
RotJFe        0.220 kg-m2   RotJMag       0.110 kg-m2   LShaft      20.000 in
sigma         3.649 psi
Wf0           0.000 W       RPM0       1000.000 rpm     NWFT         1.000
Fringing         ON         XFringe       1.000         NHx             21
CanStyle      Rotor         SCanThk       0.020 in      SCanSecs         1
pc_SCan       2.500 %       pc_Mag        0.000 %       pc_Sh        0.000 %
Ecc           0.000         UMPavg    -1.08E-14 lb      UMPmax   5.174E-13 lb
TRFrms      530.076 lb      TRFavg      470.415 lb      TRFmax     681.964 lb
CForce    78962.668 lb                                  LamThk   6.000E-03 in
NLams          2587         pcLam         3.000 %       RFei     1.000E+06

10 Core loss analysis:------------------------------------------------------

WFeCalc          OC         LossFE         Mech         XFe          1.000
DFekgS     7480.246 kg/m^3  St.Steel Hiperco 50 (7mil)
DFekgR     7480.246 kg/m^3  Ro.Steel Hiperco 50 (7mil)
DFekgSh    7480.246 kg/m^3  Sh.Steel Hiperco 50 (7mil)
wt_Teeth     64.749 lb      wt_Yoke     106.234 lb      wt_Troot    23.007 lb
Specific core losses...
cFe_E60       0.053 W/lb    cFe_H60       1.254 W/lb    cFe_60       1.307 W/lb
cFe_E_F      14.643 W/lb    cFe_H_F      20.900 W/lb    cFe_F       35.544 W/lb
cFe_T_E      20.528 W/lb    cFe_T_H      16.671 W/lb    cFe_T       37.199 W/lb
cFe_Y_E      11.364 W/lb    cFe_Y_H      17.250 W/lb    cFe_Y       28.613 W/lb
Core loss analysis...
WFe_T_E    1801.484 W       WFe_T_H    1463.003 W       WFe_T     3264.487 W
WFe_Y_E    1207.200 W       WFe_Y_H    1832.481 W       WFe_Y     3039.681 W


End of Design sheet---------------------------------------------------------
```


Template Editor
Dimensions
Config Normal RotType SurfPll Poles 8 Slots 24
Lstk 16.0 Embed Not LM 0.26 S-Slot Square
Rad3 5.75 Rad1 3.93 BetaM 150.0 SD 1.0
Stf 0.97 MagWid 1.1417 SO 0.1
MOH 0.0 SOang 30.0 TWS 0.6095
RotorAng 0.0 RadSH 2.9 TGD 0.0394 Gap 0.07
Ecc 0.0
Windings
WdgType Custom Offset 2 TC 1
NSH 70 PPATHS 8 Ext 0.0 Liner 0.009
WireSpec SFill SFg 0.4 XET 0.725 InsThick 0.0012
Skew 0.0
Control
RPM 15000.0 Vs 145.0 Drive AC Volt Connex Wye
ISP 4500.0 Sw_Ctl Generator delta 22.5
dq0 false
EMFCalc BLV RTorq On
CalcVwfm None BreakIT 0
Basic design Magnetics Calc. Options Thermal

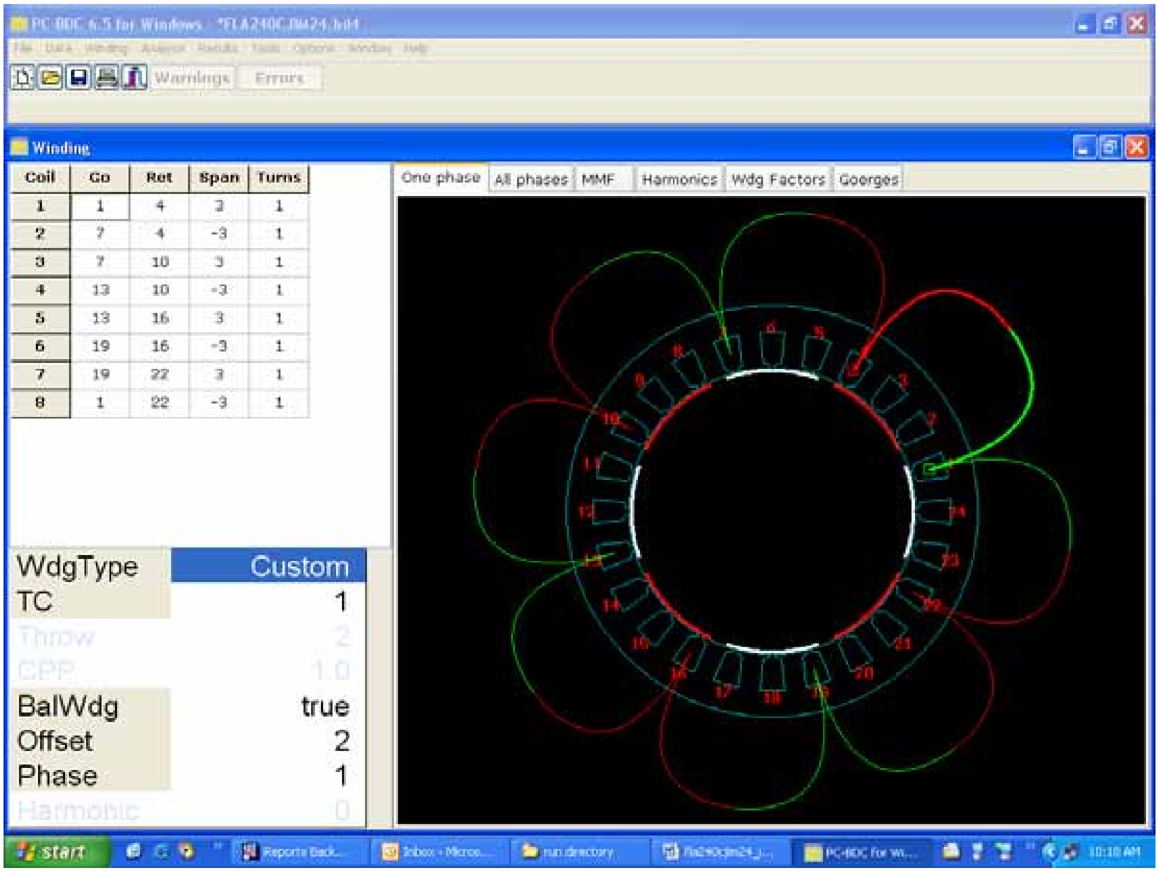

Adjustment factor for BrT
Template Editor
Magnets
XBrT 1.0 XLM 1.0 Xkm_HB 0.0 Bk 0.0
Fringing (shape of Bgap)
Fringing ON XFringe 1.0 XBetaM 1.0 BgProfil Full
RCore Iron NHx 21 NHxL 21
Leakage
Xrl 1.0 u_LKG 0.0 bBsat 0.0 apEnd 1.0
Saturation of armature-reaction and stator teeth
CalcSatn Fixed XSatn 1.0 SatnTol 0.0 Xks 0.0
Inductance
XL 1.0 XCd 1.0 XCq 1.0 XLdiff 1.0
PSSlot S-Closed Saliency Auto Lext 0.0
ETCalc BDC 6.0 XLendt 1.0 CalcLdLq Auto SpreadSO true
Resistance
X_R 1.0 Rext 0.0
Slotting, Cogging
SlotMod No CalcCogg Off PlotTooth 1 PlotPole 1
XSlotMod 1.0 XCogg 1.0 PlotYoke 1
Other adjustment factors
X_EMF 1.0 XBgap 1.0 XBtpk 1.0 Xrm 0.5
ukCL 0.0 XTTarc 1.0 XRYoke 0.0 XSYoke 0.0
XTw 0.0 LamThk 0.006 ufz 0.0
Basic design Magnetics Calc. Options Thermal



Current probe position (see Display simulation result graphs)
Template Editor
Calculation options
C-Probe Line WriteLoop None TSMin 0.0 TSMax 0.0
eDet off CalcVer cv6
R_s 0.0
Rdc 0.0 Ldc 0.0 Rac 0.0 Lac 0.0
Losses
WFeCalc OC XFe 1.0 LossFE Mech
Wf0 0.0 RPM0 1000.0 NWFT 1.0
cWmb false
Can
CanStyle Rotor
pc_Mag 0.0
TCCMag 0.0 RCanThk 0.04 RCanSecs 32 pc_RCan 2.5
pc_Sh 0.0 RCanOH1 0.0 RCanOH2 0.0 RCanTF 0.0
Additional Winding Parameters
EndFill 0.5 WireSpec2 None
WireSpecA None
TopStick false TwjWid 0.0787 TwjLeg 0.1378 TwjThk 0.015
PhsWid 0.0787 PhsLeg 0.1378 PhsThk 0.0
NumPoly 1 PolyOffs 1
FE Analysis Parameters
Basic design Magnetics Calc. Options Thermal
start



Use DegCW, HTC, or Thermal circuit to calculate temp. rise
Template Editor
Thermal
TempCalc DegCW FixTMag IterX Wdg2Mag 0.8 Ambient 120.0
T_Mag 240.0 T_Wdg 240.0 T_Brg 120.0 T_Gap 240.0
DegCW 0.01 ThTol 1.0
Specific heats and Additional thermal capacities...
cp_Frame 0.896 cp_SFe 0.45 cp_Cu 0.3831
cp_Shaft 0.45 cp_RFe 0.45 cp_Mag 0.45
AddC_F 0.0 AddC_Y 0.0 AddC_Cu 0.0
AddC_H 0.0 AddC_R 0.0 AddC_B 0.0
AddC_T 0.0 AddC_M 0.0
Additional dimensions needed for thermal model..
FrLgth 18.0 FrThk 0.1 FrDens 2700.0 CapThk 0.1
N_Fins 72.0 LFin 1.0 FinThk 0.25 XFSArea 1.0
LShaft 20.0 ShDens 7800.0
Basic design Magnetics Calc. Options Thermal
start


Warnings
Errors
Winding
Coil | Go | Ret | Span | Turns
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2 | 7 | 4 | -3 | 1
3 | 7 | 10 | 3 | 1
4 | 13 | 10 | -3 | 1
5 | 13 | 16 | 3 | 1
6 | 19 | 16 | -3 | 1
7 | 19 | 22 | 3 | 1
8 | 1 | 22 | -3 | 1
One phase
All phases
MMF
Harmonics
Wdg Factors
Goorges
WdgType Custom
TC 1
Throw 2
CPP 1.0
BalWdg true
Offset 2
Phase 1
Harmonic 0
start

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PC-BDC 6.5 for Windows (6.5.2.8) 3/8/2005 10:17:01 AM
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directory\FLA240CJIM24.bd4
Wright-Patterson AFB
PC-BDC main title
PC-BDC sub-title

1 Dimensions:---------------------------------------------------------------

RotType     SurfPll          Embed          Not          Poles            8
Stator..
StatorOD     11.500 in       LamShape    Circle          Slots           24
SYoke         0.750 in       ASD          1.000 in       SP           3.000
Rad3          5.750 in       Rad2         5.000 in       S-Slot      Square
TWS           0.610 in       SD           1.000 in       SO           0.100 in
TGD           0.039 in       SOang       30.000 mDeg     Stf          0.970
Rotor..
MOH           0.000 in       Nmbp             1          Skew         0.000
RotorOD       7.860 in       Rad1         3.930 in       Gap          0.070 in
LM            0.260 in       BetaM      150.000 eDeg     pupa         0.833
RYoke         0.770 in                                   RadSH        2.900 in
DHub          7.340 in       wNeck        0.303 in
MEdge         0.276 in       LM_min       0.260 in
wMag          2.527 in
Lstk         16.000 in       Lrotor      16.000 in       Lstator     16.330 in

2 Magnet Data:--------------------------------------------------------------

Magnet     S-L 30MGO
Br            1.140 T        Hc        1100.000 kA/m     MuRec        1.020
CBr          -0.030 %/DegC   CHc         -0.220 %/DegC   DMag      8400.000 kg/m3
BrT           1.065 T        HcT        567.600 kA/m
Nuisance      0.000 in       BrTnu        1.065 T        MuRecnu      1.020

3 Control Data:-------------------------------------------------------------

RPM       15000.000 rpm      Vs         145.000 V        Drive      AC Volt
EMFCalc         BLV          delta       22.500 eDeg     Sw_Ctl   Generator

4 Winding Data:-------------------------------------------------------------

Connex          Wye
WdgType      Custom
Offset            2          CPP          1.000
Tph           1.000          PPATHS           8          SPP          1.000
Layers        2.000          CSidesPh        16          Z           48.000
MLT          39.473 in       LgthOEnd    18.379 in       Ext          0.000 in
EndFill       0.500          LaxPack     17.396 in       Liner    9.000E-03 in
WireSpec      SFill          SFg          0.400
NSH              70          WireDia      0.044 in       InsThick 1.150E-03 in
SFg           0.400          SFn          0.600          MaxSFn       0.593
Aslot         0.531 in^2     ASlotLL      0.499 in^2     ACond        0.106 in^2
GPAslot       0.535 in^2     ATstick      0.031 in^2     TopStick     false
TwjWid        0.079 in       TwjLeg       0.138 in       TwjThk       0.015 in
PhsWid        0.079 in       PhsLeg       0.138 in       PhsThk       0.000 in
ATwj      5.315E-03 in^2     APhs         0.000 in^2
XET           0.725          ETCalc     BDC 6.0          Rext         0.000 ohm
Nse           1.273          X_R          1.000          Ax1         37.500 mDeg
T_Wdg       240.000 DegC     Rph0     5.881E-05 ohm      R_LL     1.176E-04 ohm
T_c         240.000 DegC     Rph      5.881E-05 ohm/ph   TFRho        1.865
Inductances...
Lph       1.131E-03 mH       Mph         -0.000 mH       XL           1.000
```

```
Lg        6.237E-04 mH      LSlot     3.762E-04 mH      Lendt     1.309E-04 mH
Mg           -0.000 mH      MSlot         0.000 mH      LDiff     1.195E-04 mH
Lsigma    6.266E-04 mH      Msigma    4.423E-05 mH      XLdiff        1.000
Lgg       2.780E-03 mH      Mgg          -0.001 mH      PCSlot        1.473
LL_d      2.681E-03 mH      LL_q      2.674E-03 mH      L_LL      2.678E-03 mH
Lg_0      5.043E-04 mH      Lg_2      1.242E-06 mH      Laa_d     1.132E-03 mH
Ld        1.341E-03 mH      Lq        1.337E-03 mH      Laa_q     1.130E-03 mH
Xd        8.423E-03 ohm/ph  Xq        8.400E-03 ohm/ph  Xsigma    3.659E-03 ohm/ph
XCd           1.000         XCq           1.000         Lext          0.000 mH
Gd            0.216         Gq            0.215         XLendt        1.000
kw1           1.000         Xm0           0.022 ohm/ph
ks1           1.000         kp1           1.000         kd1           1.000
ksg           0.811         fz            1.021         PSSlot     S-Closed
Saliency       Auto         CalcLdLq       Auto         muPlug        1.000
i1_Ang    -2829.896 A       i2_Ang     5659.793 A       i3_Ang    -2829.896 A

5 Magnetic Circuit Design:-----------------------------------------------------

T_Mag       240.000 DegC    T_r         240.000 DegC    XBrT          1.000
BrT           1.065 T       BgOC          0.793 T       Hca         830.695 kA/m
BgAvOC        0.653 T       PhiG         21.004 mWb     BgA/BgOC      0.824
Bg1OC         0.963 T       PhiM1        19.708 mWb     Bg1/BgOC      1.214
BmOC          0.848 T       Bm/BrT        0.796         XBtpk         1.000
HmOC       -169.305 kA/m    Hm/HcT       -0.298         PC            3.985
Bst           1.313 T       Bsy           1.340 T       Bry           1.321 T
XTw           0.000         XSYoke        0.000         XRYoke        0.000
kT            0.118 Nm/A    kE            0.129 Vs/Rad  krpmNL       15.000 krpm
kSat          1.000         XSatn         1.000         CalcSatn      Fixed
Xks           0.000         ks            0.000         XTTarc        1.000
EffWst        0.610 in      EffLst        0.847 in      ukCL          0.000
XBgap         1.000         X_EMF         1.000         k_rpf         1.000
eLLpk       203.002 V       eTmax        96.357 V       Bslot     8.723E-05 T
IBk       21943.644 A       Bk            0.000 T       Hk         -830.695 kA/m
ILR       1.233E+06 A       BmLR        -53.166 T       HmLR      -4.23E+04 kA/m
IC180     2.959E+06 A       BmC180     -128.948 T       HmC180    -1.01E+05 kA/m
BHmag       143.528 kJ/m3   Carter        1.005         Xrm           0.500
Amhp         20.212 in^2    Aghp         20.761 in^2    Rghp      1.062E+05 At/Wb
Pm0           2.531 uWb/At  Xrl           1.000         prl           0.196
apEnd         1.000         Pend          0.000         Lme           0.260 in
u_LKG         0.000         f_Lkg         0.950         if_Lkg        1.053
Fringing         ON         XFringe       1.000         XBetaM        1.000

6 Constant AC Volts static performance [phasor diagram]:-----------------------

OpMode    Generating         Vs           145.000 V       RPM       15000.000 rpm
Tshaft      475.403 lbft    Pshaft    1.012E+06 W       Eff          98.918 %
WCu        2825.787 W       WFe        6304.168 W       WWF           0.000 W
WCan        504.936 W       WMagnet       0.000 W
WTotal     9634.891 W       TempRise    120.000 DegC    Jrms       4711.357 A/in^2
IWpk       5659.793 A       IWav       3603.113 A       IWrms      4002.078 A
ILpk       5659.793 A       ILav       3603.113 A       ILrms      4002.078 A
IDC_P      6907.043 A       WFeCalc          OC         Pelec     1.002E+06 W
Eq1          87.561 V       Vph1         83.716 V       VLL1        145.000 V
Iph1       4002.078 A       Is            0.000 A
Iq1        3822.197 A       Id1        1186.354 A       gammaACV     17.244 deg
Vq1          77.343 V       Vd1          32.037 V       delta        22.500 deg
Bg1Load       0.923 T       phi          -5.256 eDeg    PF            0.996
Bqad          0.000 T       Phida1        1.272 mWb     Phiqa1        4.079 mWb
BmLoad        0.787 T       Bma          -0.061 T       Fda1       -400.535 At/gap
Tgap_PS     471.588 lbft    TEI_PS      471.438         Trel_PS       0.149 lbft
Tgap        472.206 lbft    Tei         472.056 lbft    Trel          0.149 lbft
Tloop       472.197 lbft
```

```
Vd0         204.814 V       Pelec     1.002E+06 W

8 Steady-State Thermal Model:-----------------------------------------------

TempCalc      DegCW          FixTMag       IterX          Ambient    120.000 DegC
DegCW     1.000E-02 degC/W   HTCcyl       10.000 W/m2/C   HTCend       0.000 W/m2/C
TempRise    120.000 DegC     T_c         240.000 DegC     T_r        240.000 DegC
T_f         240.000 DegC     T_y         240.000 DegC     HeatFlux     0.000 kW/m^2
SlotPeri      2.829 in       Liner     9.000E-03 in       ct_Liner     0.200 W/mC
SSArea       45.264 in^2     C_motor     112.517 kJ/C     ThRSlot  1.631E-03 C/W
FSArea      883.997 in^2

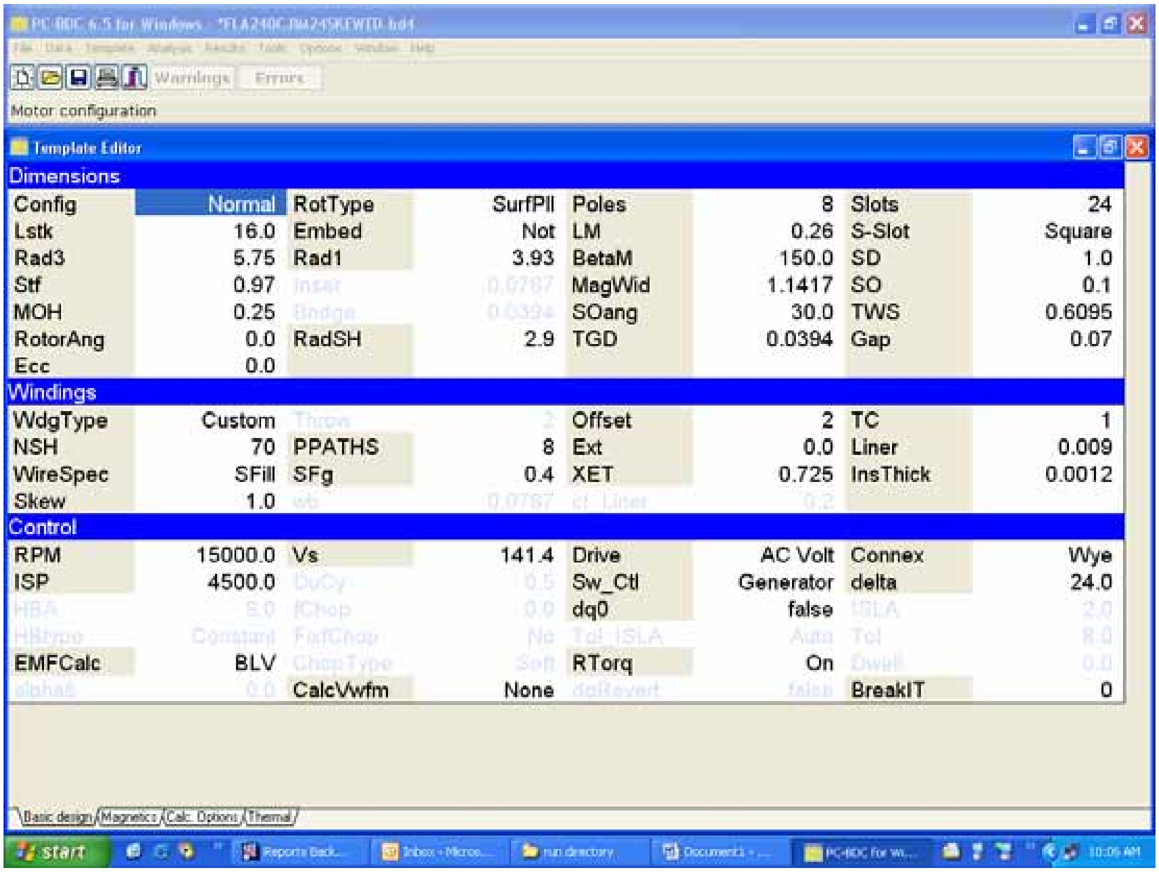
9 Miscellaneous:------------------------------------------------------------

Weights...
wt_Cu        32.307 lb       wt_Fe       239.702 lb       wt_Mag      26.012 lb
wt_Tot      298.021 lb       wt_Shaft    142.800 lb       wt_Frame    39.567 lb
wt_FeS      170.983 lb       wt_FeR       68.719 lb       wt_RSS     238.360 lb
Inertia components...
RotJ          0.506 kg-m2    RotJSS        0.509 kg-m2    RotJSh       0.176 kg-m2
RotJFe        0.220 kg-m2    RotJMag       0.110 kg-m2    LShaft      20.000 in
sigma         3.649 psi
Wf0           0.000 W        RPM0       1000.000 rpm      NWFT         1.000
Fringing         ON          XFringe       1.000          NHx             21
CanStyle      Rotor          SCanThk       0.020 in       SCanSecs         1
pc_SCan       2.500 %        pc_Mag        0.000 %        pc_Sh        0.000 %
Ecc           0.000          UMPavg    -1.08E-14 lb       UMPmax   5.174E-13 lb
TRFrms      530.076 lb       TRFavg      470.415 lb       TRFmax     681.964 lb
CForce    78962.668 lb                                    LamThk   6.000E-03 in
NLams          2587          pcLam         3.000 %        RFei     1.000E+06

10 Core loss analysis:------------------------------------------------------

WFeCalc          OC          LossFE         Mech          XFe          1.000
DFekgS     7480.246 kg/m^3   St.Steel Hiperco 50 (7mil)
DFekgR     7480.246 kg/m^3   Ro.Steel Hiperco 50 (7mil)
DFekgSh    7480.246 kg/m^3   Sh.Steel Hiperco 50 (7mil)
wt_Teeth     64.749 lb       wt_Yoke     106.234 lb       wt_Troot    23.007 lb
Specific core losses...
cFe_E60       0.053 W/lb     cFe_H60       1.254 W/lb     cFe_60       1.307 W/lb
cFe_E_F      14.643 W/lb     cFe_H_F      20.900 W/lb     cFe_F       35.544 W/lb
cFe_T_E      20.528 W/lb     cFe_T_H      16.671 W/lb     cFe_T       37.199 W/lb
cFe_Y_E      11.364 W/lb     cFe_Y_H      17.250 W/lb     cFe_Y       28.613 W/lb
Core loss analysis...
WFe_T_E    1801.484 W        WFe_T_H    1463.003 W        WFe_T     3264.487 W
WFe_Y_E    1207.200 W        WFe_Y_H    1832.481 W        WFe_Y     3039.681 W


End of Design sheet---------------------------------------------------------
```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File Data Template Analysis Results Tools Options Window Help
Warnings Errors
Motor configuration
Template Editor
Dimensions
Config Normal RotType SurfPll Poles 8 Slots 24
Lstk 16.0 Embed Not LM 0.26 S-Slot Square
Rad3 5.75 Rad1 3.93 BetaM 150.0 SD 1.0
Stf 0.97 Inset 0.0787 MagWid 1.1417 SO 0.1
MOH 0.25 Bridge 0.0394 SOang 30.0 TWS 0.6095
RotorAng 0.0 RadSH 2.9 TGD 0.0394 Gap 0.07
Ecc 0.0
Windings
WdgType Custom Throw 2 Offset 2 TC 1
NSH 70 PPATHS 8 Ext 0.0 Liner 0.009
WireSpec SFill SFg 0.4 XET 0.725 InsThick 0.0012
Skew 1.0 wb 0.0787 cl_Liner 0.2
Control
RPM 15000.0 Vs 141.4 Drive AC Volt Connex Wye
ISP 4500.0 DuCy 0.5 Sw_Ctl Generator delta 24.0
HBA 6.0 IChop 0.0 dq0 false ISLA 2.0
HBtype Constant FixfChop No Tol_ISLA Auto Tol 8.0
EMFCalc BLV ChopType Soft RTorq On Dwell 0.0
alpha6 0.0 CalcVwfm None dqRevert false BreakIT 0
Basic design Magnetics Calc. Options Thermal
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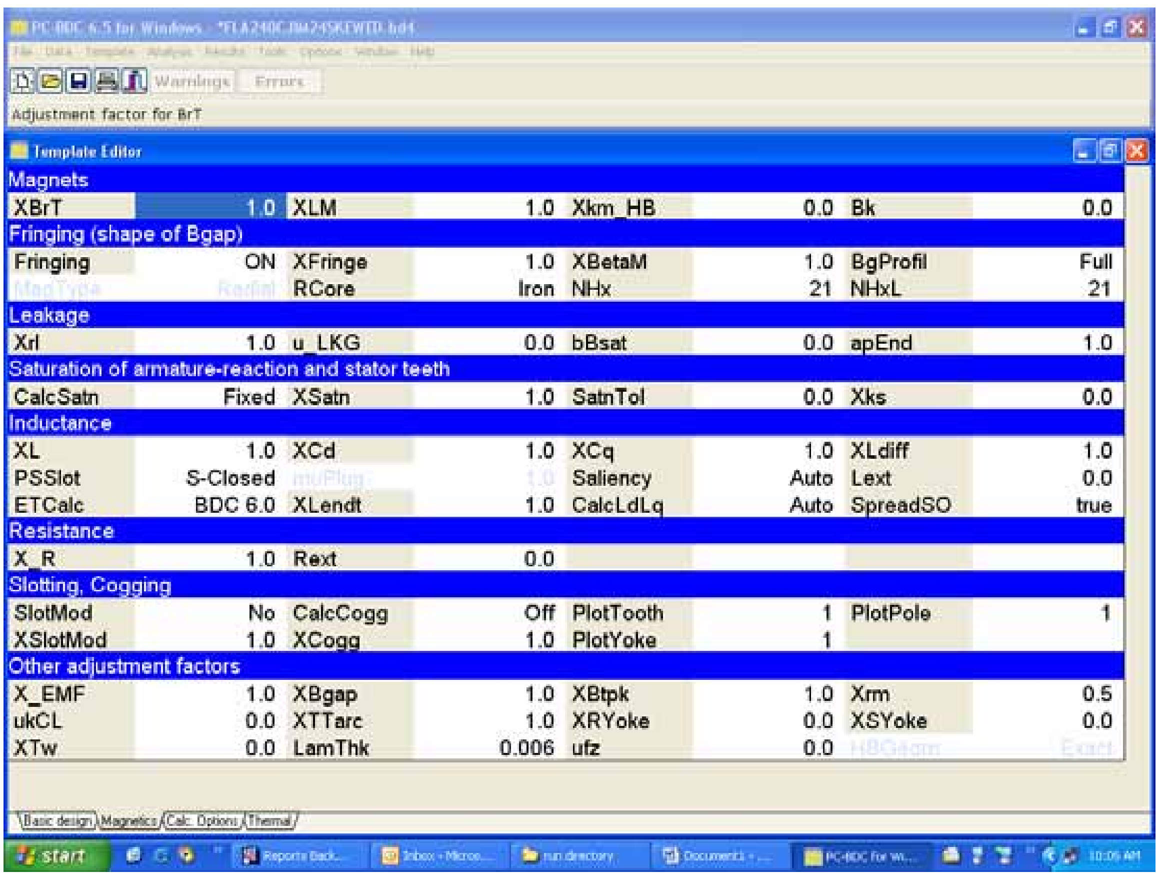
PC-BDC 6.5 for Windows - *FLA240C.JM24SKEWTD.bd4
File Data Template Analysis Results Tools Options Window Help
Warnings Errors
Adjustment factor for BrT
Template Editor
Magnets
XBrT 1.0 XLM 1.0 Xkm_HB 0.0 Bk 0.0
Fringing (shape of Bgap)
Fringing ON XFringe 1.0 XBetaM 1.0 BgProfil Full
MagType Radial RCore Iron NHx 21 NHxL 21
Leakage
Xrl 1.0 u_LKG 0.0 bBsat 0.0 apEnd 1.0
Saturation of armature-reaction and stator teeth
CalcSatn Fixed XSatn 1.0 SatnTol 0.0 Xks 0.0
Inductance
XL 1.0 XCd 1.0 XCq 1.0 XLdiff 1.0
PSSlot S-Closed muPlug 1.0 Saliency Auto Lext 0.0
ETCalc BDC 6.0 XLendt 1.0 CalcLdLq Auto SpreadSO true
Resistance
X_R 1.0 Rext 0.0
Slotting, Cogging
SlotMod No CalcCogg Off PlotTooth 1 PlotPole 1
XSlotMod 1.0 XCogg 1.0 PlotYoke 1
Other adjustment factors
X_EMF 1.0 XBgap 1.0 XBtpk 1.0 Xrm 0.5
ukCL 0.0 XTTarc 1.0 XRYoke 0.0 XSYoke 0.0
XTw 0.0 LamThk 0.006 ufz 0.0 HBGapm Exact
Basic design Magnetics Calc. Options Thermal
start
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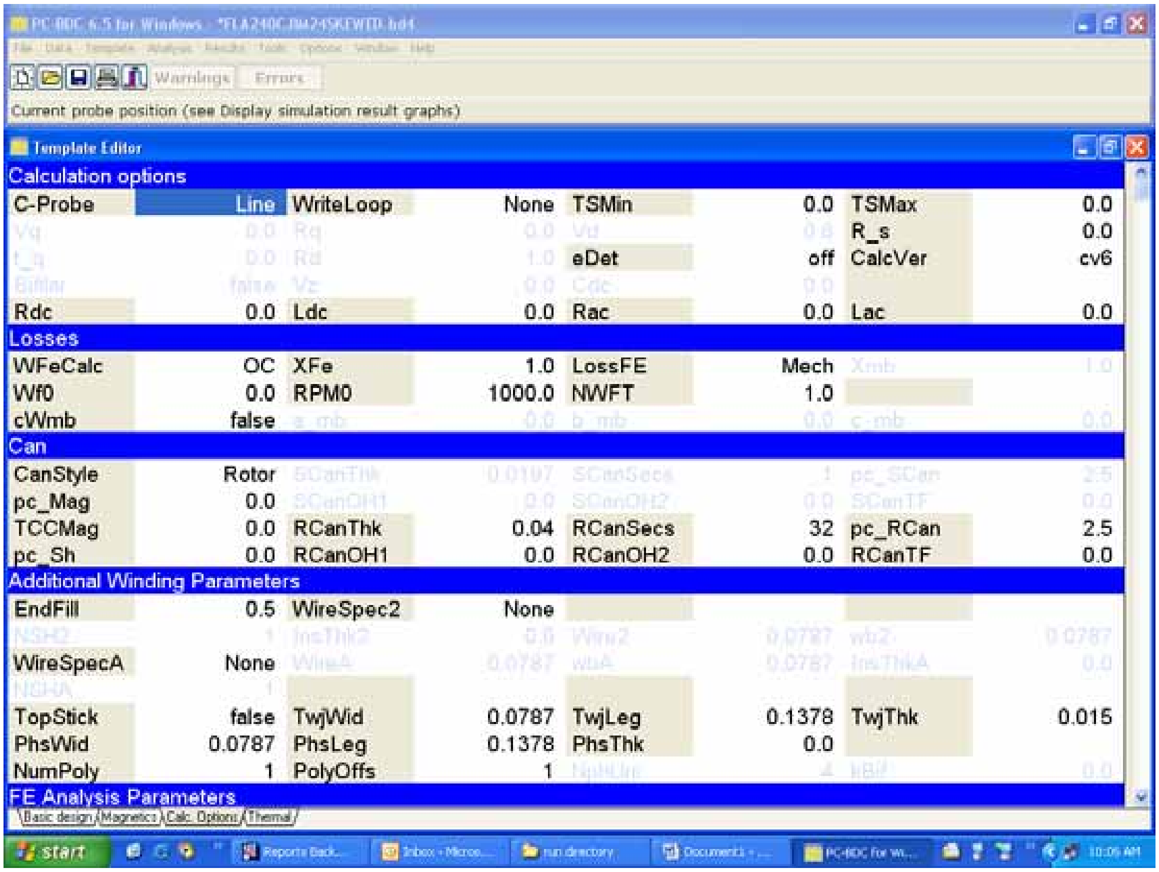
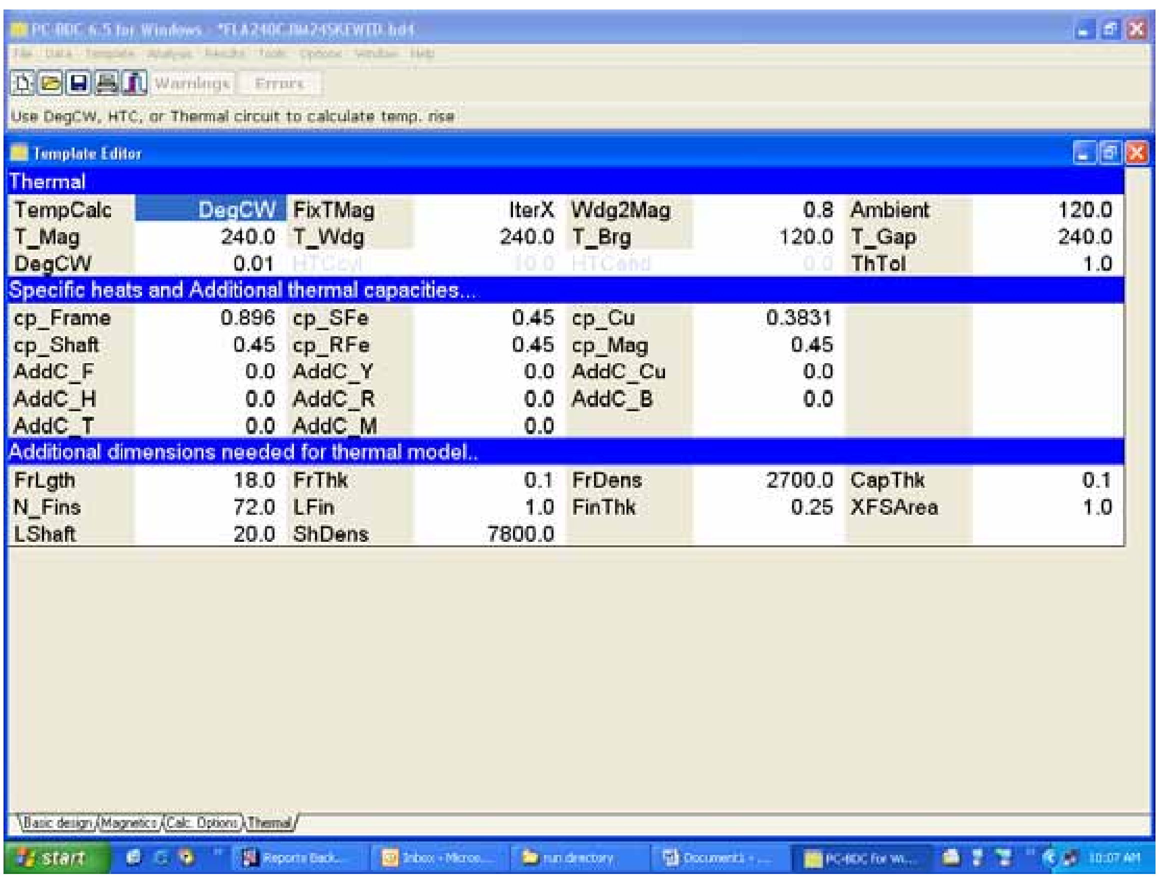


Current probe position (see Display simulation result graphs)
Template Editor
Calculation options
C-Probe Line WriteLoop None TSMin 0.0 TSMax 0.0
R_s 0.0
eDet off CalcVer cv6
Rdc 0.0 Ldc 0.0 Rac 0.0 Lac 0.0
Losses
WFeCalc OC XFe 1.0 LossFE Mech
Wf0 0.0 RPM0 1000.0 NWFT 1.0
cWmb false
Can
CanStyle Rotor
pc_Mag 0.0
TCCMag 0.0 RCanThk 0.04 RCanSecs 32 pc_RCan 2.5
pc_Sh 0.0 RCanOH1 0.0 RCanOH2 0.0 RCanTF 0.0
Additional Winding Parameters
EndFill 0.5 WireSpec2 None
WireSpecA None
TopStick false TwjWid 0.0787 TwjLeg 0.1378 TwjThk 0.015
PhsWid 0.0787 PhsLeg 0.1378 PhsThk 0.0
NumPoly 1 PolyOffs 1
FE Analysis Parameters
Basic design Magnetics Calc. Options Thermal
start



Use DegCW, HTC, or Thermal circuit to calculate temp. rise
Template Editor
Thermal
TempCalc DegCW FixTMag IterX Wdg2Mag 0.8 Ambient 120.0
T_Mag 240.0 T_Wdg 240.0 T_Brg 120.0 T_Gap 240.0
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FrLgth 18.0 FrThk 0.1 FrDens 2700.0 CapThk 0.1
N_Fins 72.0 LFin 1.0 FinThk 0.25 XFSArea 1.0
LShaft 20.0 ShDens 7800.0
Basic design Magnetics Calc. Options Thermal
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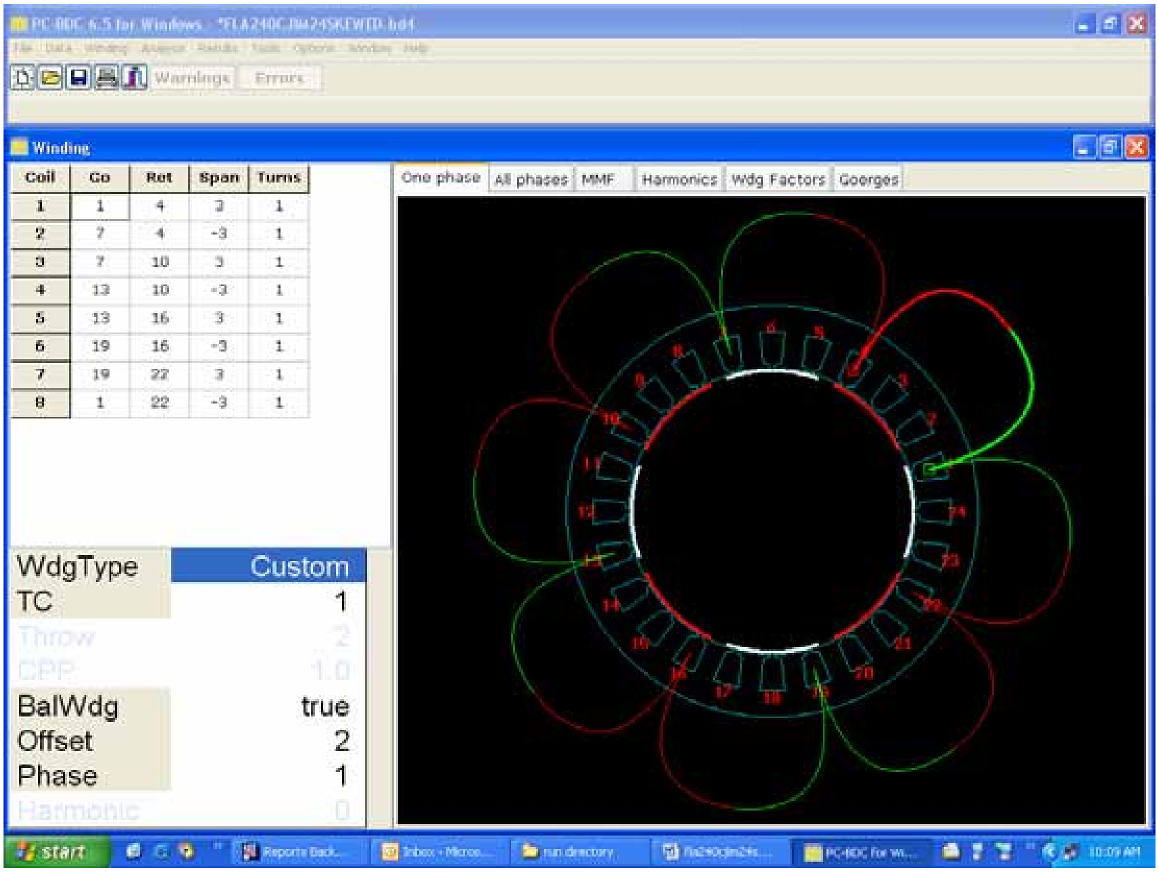
PC-BDC 6.5 for Windows
Warnings
Errors
Winding
Coil Go Ret Span Turns
1 1 4 3 1
2 7 4 -3 1
3 7 10 3 1
4 13 10 -3 1
5 13 16 3 1
6 19 16 -3 1
7 19 22 3 1
8 1 22 -3 1
One phase
All phases
MMF
Harmonics
Wdg Factors
Goerges
WdgType Custom
TC 1
Throw 2
CPP 1.0
BalWdg true
Offset 2
Phase 1
Harmonic 0
start

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directory\FLA240CJIM24SKEWED.bd4
Wright-Patterson AFB
PC-BDC main title
PC-BDC sub-title

1 Dimensions:--------------------------------------------------------------

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Rad3          5.750 in        Rad2           5.000 in       S-Slot        Square
TWS           0.610 in        SD             1.000 in       SO             0.100 in
TGD           0.039 in        SOang         30.000 mDeg     Stf            0.970
Rotor..
MOH           0.250 in        Nmbp               1          Skew           1.000
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LM            0.260 in        BetaM        150.000 eDeg     pupa           0.833
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DHub          7.340 in        wNeck          0.303 in
MEdge         0.276 in        LM_min         0.260 in
wMag          2.527 in
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BrT           1.065 T         HcT          567.600 kA/m
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WdgType      Custom
Offset            2           CPP            1.000
Tph           1.000           PPATHS             8          SPP            1.000
Layers        2.000           CSidesPh          16          Z             48.000
MLT          39.473 in        LgthOEnd      18.379 in       Ext            0.000 in
EndFill       0.500           LaxPack       17.396 in       Liner      9.000E-03 in
WireSpec      SFill           SFg            0.400
NSH              70           WireDia        0.044 in       InsThick   1.150E-03 in
SFg           0.400           SFn            0.600          MaxSFn         0.593
Aslot         0.531 in^2      ASlotLL        0.499 in^2     ACond          0.106 in^2
GPAslot       0.535 in^2      ATstick        0.031 in^2     TopStick       false
TwjWid        0.079 in        TwjLeg         0.138 in       TwjThk         0.015 in
PhsWid        0.079 in        PhsLeg         0.138 in       PhsThk         0.000 in
ATwj      5.315E-03 in^2      APhs           0.000 in^2
XET           0.725           ETCalc       BDC 6.0          Rext           0.000 ohm
Nse           1.216           X_R            1.000          Ax1           45.000 mDeg
T_Wdg       240.000 DegC      Rph0       5.881E-05 ohm      R_LL       1.176E-04 ohm
T_c         240.000 DegC      Rph        5.881E-05 ohm/ph   TFRho          1.865
Inductances...
Lph       1.131E-03 mH        Mph           -0.000 mH       XL             1.000
```

Lg	6.237E-04	mH	LSlot	3.762E-04	mH	Lendt	1.309E-04	mH
Mg	-0.000	mH	MSlot	0.000	mH	LDiff	1.639E-04	mH
Lsigma	6.710E-04	mH	Msigma	2.201E-05	mH	XLdiff	1.000	
Lgg	2.780E-03	mH	Mgg	-0.001	mH	PCSlot	1.473	
LL_d	2.681E-03	mH	LL_q	2.674E-03	mH	L_LL	2.678E-03	mH
Lg_0	4.599E-04	mH	Lg_2	1.132E-06	mH	Laa_d	1.132E-03	mH
Ld	1.340E-03	mH	Lq	1.337E-03	mH	Laa_q	1.130E-03	mH
Xd	8.422E-03	ohm/ph	Xq	8.401E-03	ohm/ph	Xsigma	4.078E-03	ohm/ph
XCd	1.000		XCq	1.000		Lext	0.000	mH
Gd	0.216		Gq	0.215		XLendt	1.000	
kw1	0.955		Xm0	0.020	ohm/ph			
ks1	0.955		kp1	1.000		kd1	1.000	
ksg	0.739		fz	1.021		PSSlot	S-Closed	
Saliency	Auto		CalcLdLq	Auto		muPlug	1.000	
i1_Ang	7.216E-13	A	i2_Ang	5102.866	A	i3_Ang	-5102.866	A

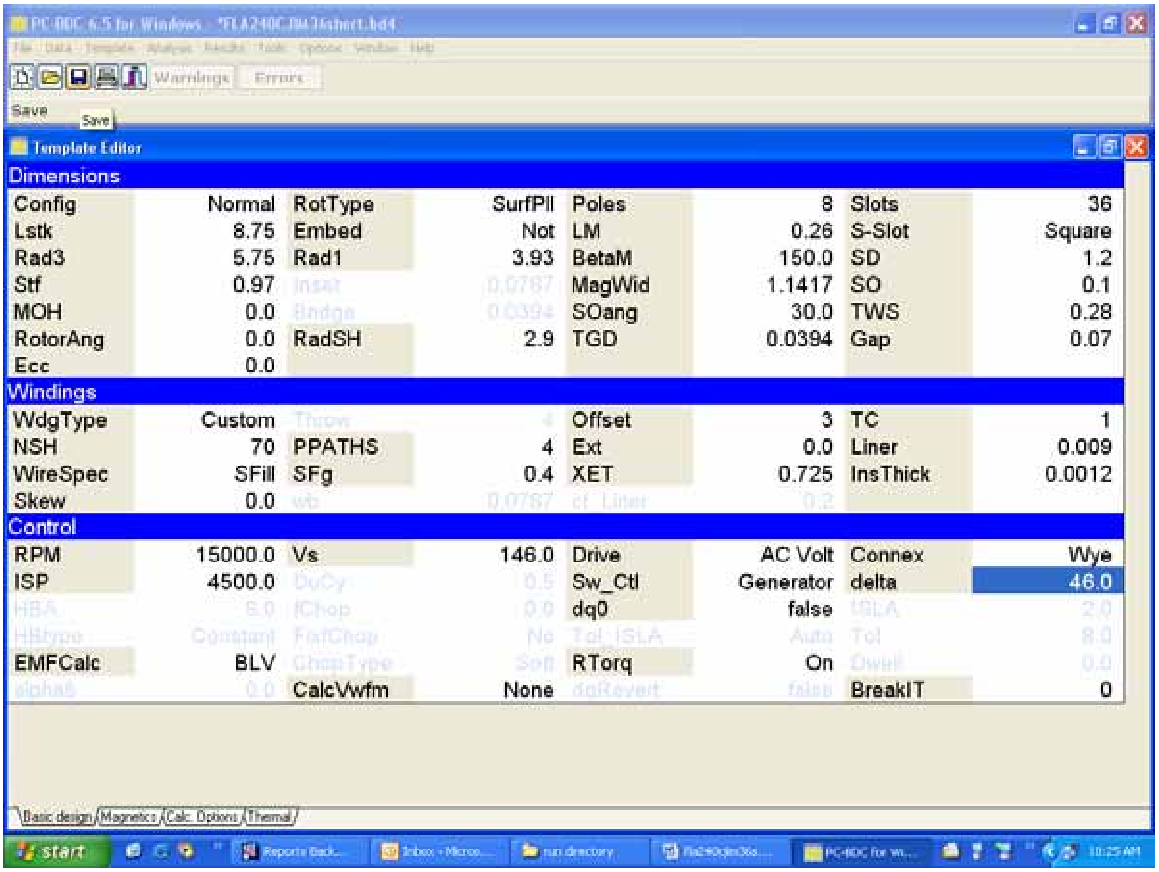
5 Magnetic Circuit Design:---

T_Mag	240.000	DegC	T_r	240.000	DegC	XBrT	1.000	
BrT	1.065	T	BgOC	0.813	T	Hca	830.695	kA/m
BgAvOC	0.670	T	PhiG	21.523	mWb	BgA/BgOC	0.824	
Bg1OC	0.987	T	PhiM1	20.196	mWb	Bg1/BgOC	1.214	
BmOC	0.842	T	Bm/BrT	0.791		XBtpk	1.000	
HmOC	-173.483	kA/m	Hm/HcT	-0.306		PC	3.864	
Bst	1.342	T	Bsy	1.370	T	Bry	1.354	T
XTw	0.000		XSYoke	0.000		XRYoke	0.000	
kT	0.116	Nm/A	kE	0.132	Vs/Rad	krpmNL	15.000	krpm
kSat	1.000		XSatn	1.000		CalcSatn	Fixed	
Xks	0.000		ks	0.000		XTTarc	1.000	
EffWst	0.610	in	EffLst	0.847	in	ukCL	0.000	
XBgap	1.000		X_EMF	1.000		k_rpf	1.000	
eLLpk	207.794	V	eTmax	75.364	V	Bslot	8.995E-05	T
IBk	21943.644	A	Bk	0.000	T	Hk	-830.695	kA/m
ILR	1.202E+06	A	BmLR	-51.239	T	HmLR	-4.08E+04	kA/m
IC180	2.969E+06	A	BmC180	-127.937	T	HmC180	-1.01E+05	kA/m
BHmag	146.141	kJ/m3	Carter	1.005		Xrm	0.500	
Amhp	20.844	in^2	Aghp	20.761	in^2	Rghp	1.062E+05	At/Wb
Pm0	2.610	uWb/At	Xrl	1.000		prl	0.190	
apEnd	1.000		Pend	0.000		Lme	0.260	in
u_LKG	0.000		f_Lkg	0.950		if_Lkg	1.053	
Fringing	ON		XFringe	1.000		XBetaM	1.000	

6 Constant AC Volts static performance [phasor diagram]:-----------------------

OpMode	Generating		Vs	141.400	V	RPM	15000.000	rpm
Tshaft	481.992	lbft	Pshaft	1.027E+06	W	Eff	98.935	%
WCu	3062.707	W	WFe	6564.507	W	WWF	0.000	W
WCan	530.223	W	WMagnet	0.000	W			
WTotal	10157.437	W	TempRise	120.000	DegC	Jrms	4904.887	A/in^2
IWpk	5892.282	A	IWav	3751.120	A	IWrms	4166.473	A
ILpk	5892.282	A	ILav	3751.120	A	ILrms	4166.473	A
IDC_P	7182.242	A	WFeCalc	OC		Pelec	1.016E+06	W
Eq1	85.683	V	Vph1	81.637	V	VLL1	141.400	V
Iph1	4166.473	A	Is	0.000	A			
Iq1	3961.518	A	Id1	1290.684	A	gammaACV	18.046	deg
Vq1	74.579	V	Vd1	33.205	V	delta	24.000	deg
Bg1Load	0.943	T	phi	-5.954	eDeg	PF	0.995	
Bqad	0.000	T	Phida1	1.322	mWb	Phiqa1	4.037	mWb
BmLoad	0.779	T	Bma	-0.063	T	Fda1	-416.119	At/gap
Tgap_PS	478.295	lbft	TEI_PS	478.141		Trel_PS	0.154	lbft
Tgap	478.661	lbft	Tei	478.507	lbft	Trel	0.154	lbft
Tloop	478.652	lbft						

```
Vd0          200.420 V        Pelec     1.016E+06 W

8 Steady-State Thermal Model:--------------------------------------------------

TempCalc       DegCW          FixTMag       IterX          Ambient    120.000 DegC
DegCW      1.000E-02 degC/W   HTCcyl       10.000 W/m2/C   HTCend       0.000 W/m2/C
TempRise     120.000 DegC     T_c         240.000 DegC     T_r        240.000 DegC
T_f          240.000 DegC     T_y         240.000 DegC     HeatFlux     0.000 kW/m^2
SlotPeri       2.829 in       Liner     9.000E-03 in       ct_Liner     0.200 W/mC
SSArea        45.264 in^2     C_motor     113.121 kJ/C     ThRSlot  1.631E-03 C/W
FSArea       883.997 in^2

9 Miscellaneous:---------------------------------------------------------------

Weights...
wt_Cu         32.307 lb       wt_Fe       241.850 lb       wt_Mag      26.825 lb
wt_Tot       300.982 lb       wt_Shaft    142.800 lb       wt_Frame    39.567 lb
wt_FeS       170.983 lb       wt_FeR       70.867 lb       wt_RSS     241.347 lb
Inertia components...
RotJ           0.516 kg-m2    RotJSS        0.520 kg-m2    RotJSh       0.176 kg-m2
RotJFe         0.227 kg-m2    RotJMag       0.113 kg-m2    LShaft      20.000 in
sigma          3.699 psi
Wf0            0.000 W        RPM0       1000.000 rpm      NWFT         1.000
Fringing          ON          XFringe       1.000          NHx             21
CanStyle       Rotor          SCanThk       0.020 in       SCanSecs         1
pc_SCan        2.500 %        pc_Mag        0.000 %        pc_Sh        0.000 %
Ecc            0.000          UMPavg    -5.78E-15 lb       UMPmax   3.134E-13 lb
TRFrms       514.345 lb       TRFavg      445.463 lb       TRFmax     716.117 lb
CForce     81430.252 lb                                    LamThk   6.000E-03 in
NLams           2587          pcLam         3.000 %        RFei     1.000E+06

10 Core loss analysis:---------------------------------------------------------

WFeCalc           OC          LossFE         Mech          XFe          1.000
DFekgS      7480.246 kg/m^3   St.Steel Hiperco 50 (7mil)
DFekgR      7480.246 kg/m^3   Ro.Steel Hiperco 50 (7mil)
DFekgSh     7480.246 kg/m^3   Sh.Steel Hiperco 50 (7mil)
wt_Teeth      64.749 lb       wt_Yoke     106.234 lb       wt_Troot    23.007 lb
Specific core losses...
cFe_E60        0.053 W/lb     cFe_H60       1.254 W/lb     cFe_60       1.307 W/lb
cFe_E_F       14.643 W/lb     cFe_H_F      20.900 W/lb     cFe_F       35.544 W/lb
cFe_T_E       21.450 W/lb     cFe_T_H      17.305 W/lb     cFe_T       38.755 W/lb
cFe_Y_E       11.874 W/lb     cFe_Y_H      17.905 W/lb     cFe_Y       29.779 W/lb
Core loss analysis...
WFe_T_E     1882.337 W        WFe_T_H    1518.631 W        WFe_T     3400.968 W
WFe_Y_E     1261.381 W        WFe_Y_H    1902.158 W        WFe_Y     3163.539 W


End of Design sheet------------------------------------------------------------
```



PC-BDC 6.5 for Windows - *FLA240C.Jbk34short.bd4

Save

Template Editor

Dimensions

Config	Normal	RotType	SurfPll	Poles	8	Slots	36
Lstk	8.75	Embed	Not	LM	0.26	S-Slot	Square
Rad3	5.75	Rad1	3.93	BetaM	150.0	SD	1.2
Stf	0.97	Inset	0.0787	MagWid	1.1417	SO	0.1
MOH	0.0	Bridge	0.0394	SOang	30.0	TWS	0.28
RotorAng	0.0	RadSH	2.9	TGD	0.0394	Gap	0.07
Ecc	0.0						

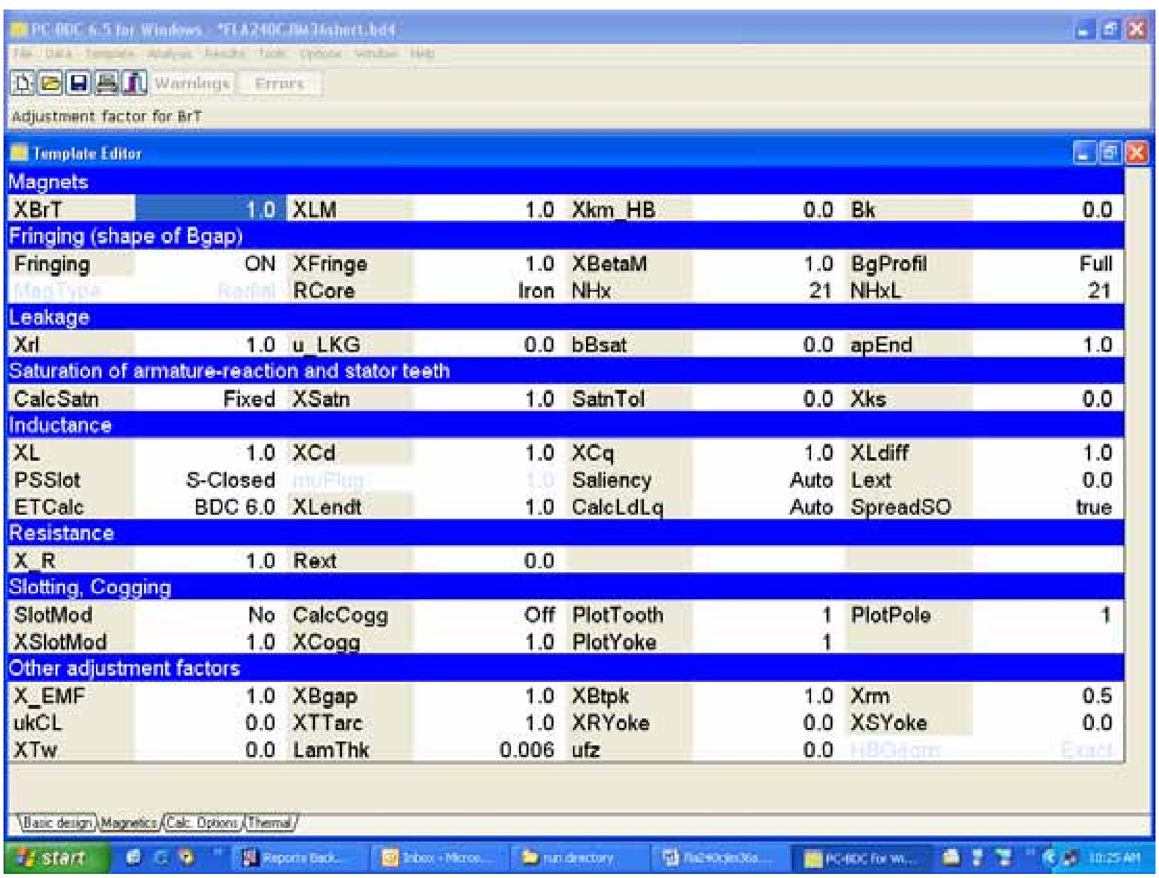
Windings

WdgType	Custom	Throw	4	Offset	3	TC	1
NSH	70	PPATHS	4	Ext	0.0	Liner	0.009
WireSpec	SFill	SFg	0.4	XET	0.725	InsThick	0.0012
Skew	0.0	wb	0.0787	cl_Liner	0.2		

Control

RPM	15000.0	Vs	146.0	Drive	AC Volt	Connex	Wye
ISP	4500.0	DuCy	0.5	Sw_Ctl	Generator	delta	46.0
HBA	6.0	IChop	0.0	dq0	false	ISLA	2.0
HBtype	Constant	FixtChop	No	Tol_ISLA	Auto	Tol	8.0
EMFCalc	BLV	ChopType	Soft	RTorq	On	Dwell	0.0
alphaB	0.0	CalcVwfm	None	dqRevert	false	BreakIT	0

Basic design / Magnetics / Calc. Options / Thermal



PC-BDC 6.5 for Windows - *FLA240C.Jbk34short.bd4

Adjustment factor for BrT

Template Editor

Magnets

XBrT	1.0	XLM	1.0	Xkm_HB	0.0	Bk	0.0

Fringing (shape of Bgap)

Fringing	ON	XFringe	1.0	XBetaM	1.0	BgProfil	Full
MagType	Radial	RCore	Iron	NHx	21	NHxL	21

Leakage

Xrl	1.0	u_LKG	0.0	bBsat	0.0	apEnd	1.0

Saturation of armature-reaction and stator teeth

CalcSatn	Fixed	XSatn	1.0	SatnTol	0.0	Xks	0.0

Inductance

XL	1.0	XCd	1.0	XCq	1.0	XLdiff	1.0
PSSlot	S-Closed	muPlug	1.0	Saliency	Auto	Lext	0.0
ETCalc	BDC 6.0	XLendt	1.0	CalcLdLq	Auto	SpreadSO	true

Resistance

X_R	1.0	Rext	0.0				

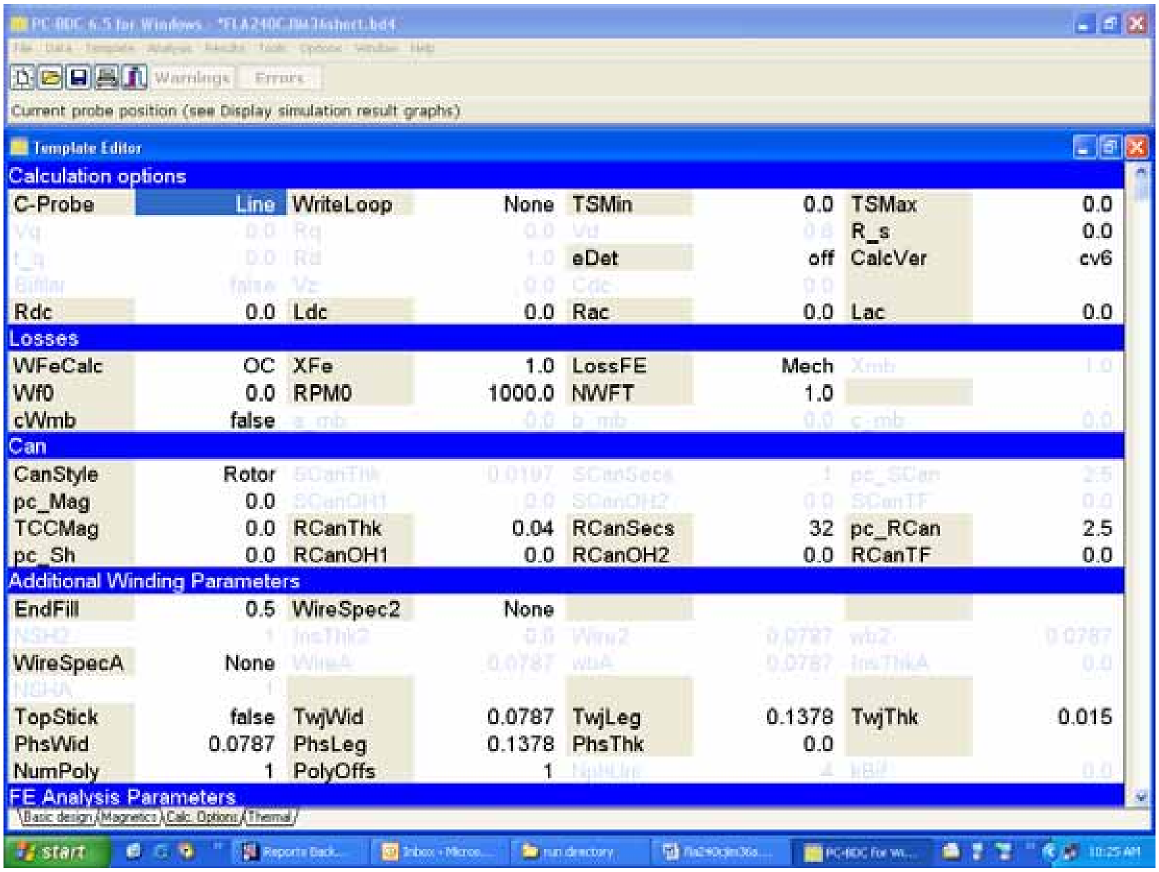
Slotting, Cogging

SlotMod	No	CalcCogg	Off	PlotTooth	1	PlotPole	1
XSlotMod	1.0	XCogg	1.0	PlotYoke	1		

Other adjustment factors

X_EMF	1.0	XBgap	1.0	XBtpk	1.0	Xrm	0.5
ukCL	0.0	XTTarc	1.0	XRYoke	0.0	XSYoke	0.0
XTw	0.0	LamThk	0.006	ufz	0.0	HBGeom	Exact

Basic design / Magnetics / Calc. Options / Thermal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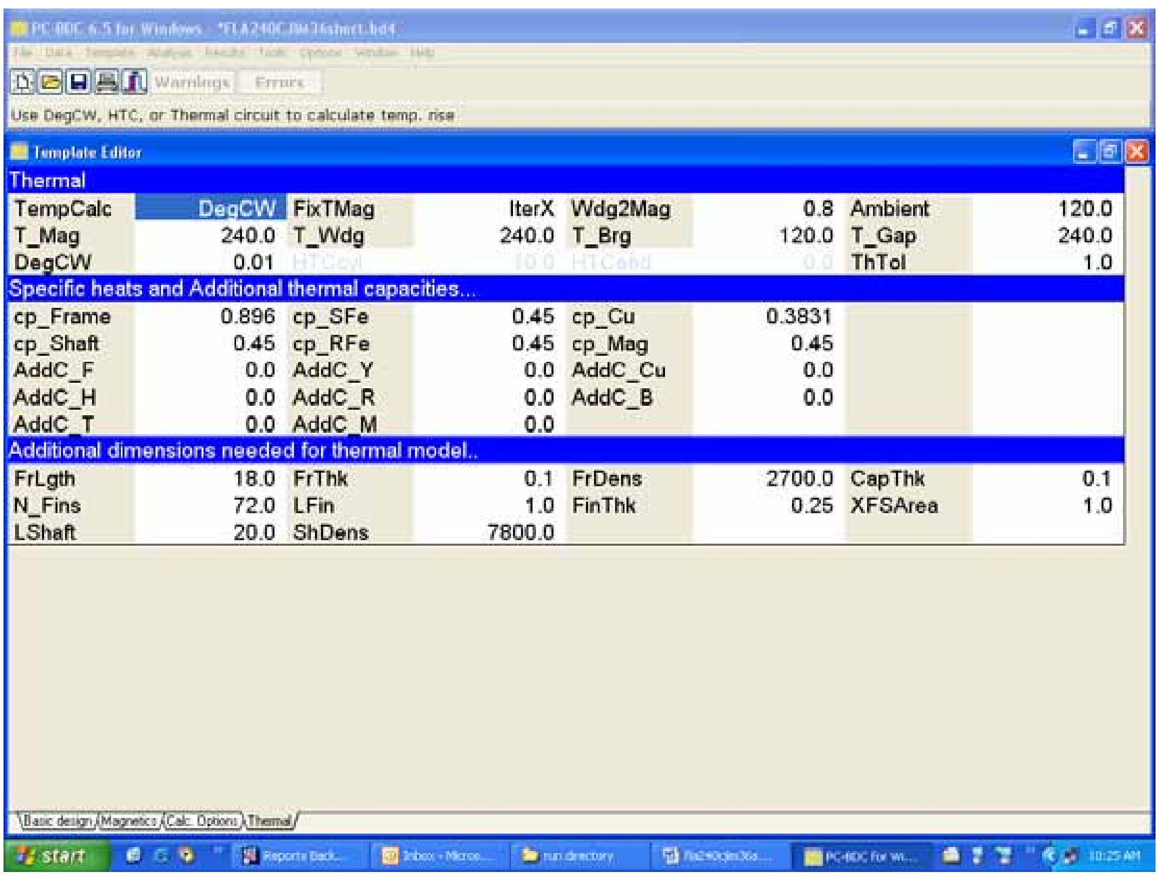
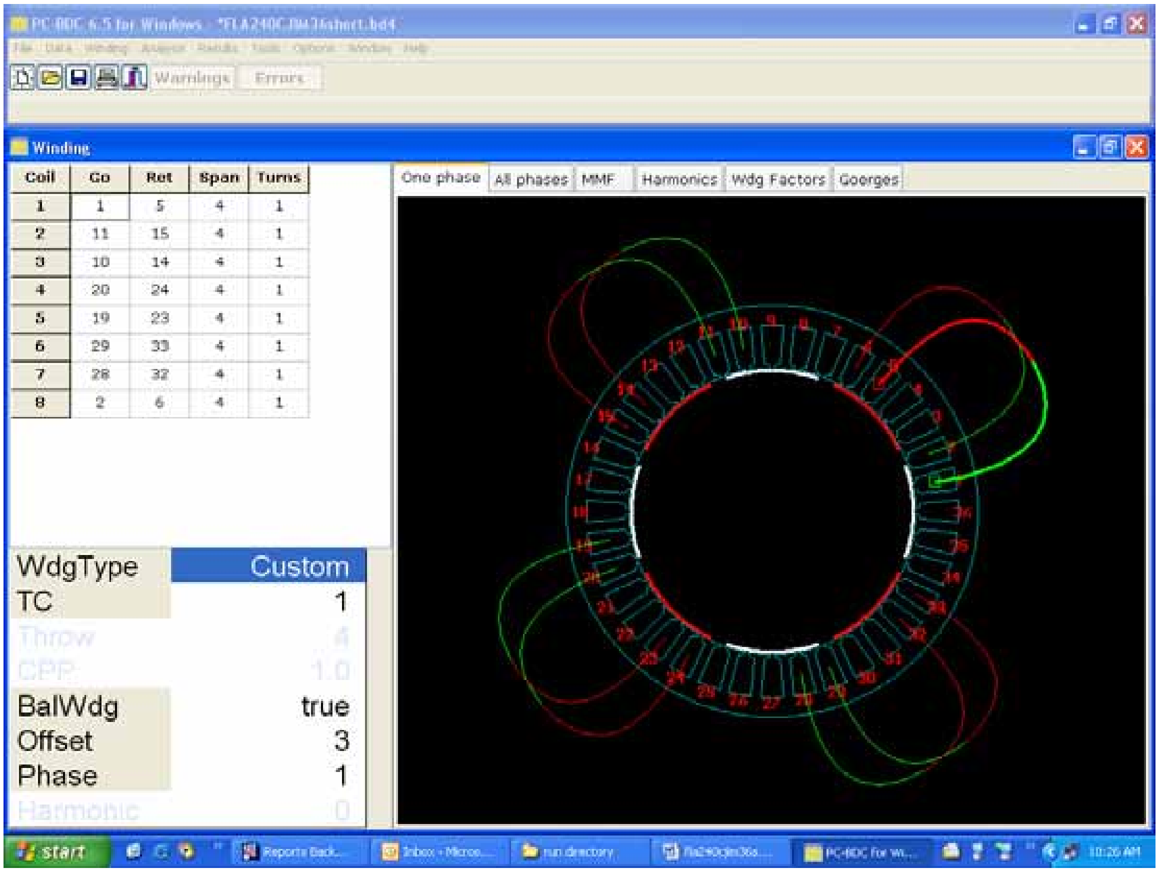
Warnings
Errors
Current probe position (see Display simulation result graphs)
Template Editor
Calculation options
C-Probe Line WriteLoop None TSMin 0.0 TSMax 0.0
R_s 0.0
eDet off CalcVer cv6
Rdc 0.0 Ldc 0.0 Rac 0.0 Lac 0.0
Losses
WFeCalc OC XFe 1.0 LossFE Mech
Wf0 0.0 RPM0 1000.0 NWFT 1.0
cWmb false
Can
CanStyle Rotor
pc_Mag 0.0
TCCMag 0.0 RCanThk 0.04 RCanSecs 32 pc_RCan 2.5
pc_Sh 0.0 RCanOH1 0.0 RCanOH2 0.0 RCanTF 0.0
Additional Winding Parameters
EndFill 0.5 WireSpec2 None
WireSpecA None
TopStick false TwjWid 0.0787 TwjLeg 0.1378 TwjThk 0.015
PhsWid 0.0787 PhsLeg 0.1378 PhsThk 0.0
NumPoly 1 PolyOffs 1
FE Analysis Parameters
Basic design Magnetics Calc. Options Thermal
start


PC-BDC 6.5 for Windows - *FLA240CJM34short.bd4
Warnings
Errors
Use DegCW, HTC, or Thermal circuit to calculate temp. rise
Template Editor
Thermal
TempCalc DegCW FixTMag IterX Wdg2Mag 0.8 Ambient 120.0
T_Mag 240.0 T_Wdg 240.0 T_Brg 120.0 T_Gap 240.0
DegCW 0.01 ThTol 1.0
Specific heats and Additional thermal capacities...
cp_Frame 0.896 cp_SFe 0.45 cp_Cu 0.3831
cp_Shaft 0.45 cp_RFe 0.45 cp_Mag 0.45
AddC_F 0.0 AddC_Y 0.0 AddC_Cu 0.0
AddC_H 0.0 AddC_R 0.0 AddC_B 0.0
AddC_T 0.0 AddC_M 0.0
Additional dimensions needed for thermal model..
FrLgth 18.0 FrThk 0.1 FrDens 2700.0 CapThk 0.1
N_Fins 72.0 LFin 1.0 FinThk 0.25 XFSArea 1.0
LShaft 20.0 ShDens 7800.0
Basic design Magnetics Calc. Options Thermal
start



Winding
Coil
Go
Ret
Span
Turns
1 1 5 4 1
2 11 15 4 1
3 10 14 4 1
4 20 24 4 1
5 19 23 4 1
6 29 33 4 1
7 28 32 4 1
8 2 6 4 1
One phase
All phases
MMF
Harmonics
Wdg Factors
Goerges
WdgType Custom
TC 1
Throw 4
CPP 1.0
BalWdg true
Offset 3
Phase 1
Harmonic 0

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directory\FLA240CJIM36short.bd4
Wright-Patterson AFB
PC-BDC main title
PC-BDC sub-title

1 Dimensions:-------------------------------------------------------------

RotType     SurfPll           Embed             Not         Poles              8
Stator..
StatorOD     11.500 in        LamShape       Circle         Slots             36
SYoke         0.550 in        ASD             1.200 in      SP             4.500
Rad3          5.750 in        Rad2            5.200 in      S-Slot        Square
TWS           0.280 in        SD              1.200 in      SO             0.100 in
TGD           0.039 in        SOang          30.000 mDeg    Stf            0.970
Rotor..
MOH           0.000 in        Nmbp                1         Skew           0.000
RotorOD       7.860 in        Rad1            3.930 in      Gap            0.070 in
LM            0.260 in        BetaM         150.000 eDeg    pupa           0.833
RYoke         0.770 in                                      RadSH          2.900 in
DHub          7.340 in        wNeck           0.303 in
MEdge         0.276 in        LM_min          0.260 in
wMag          2.527 in
Lstk          8.750 in        Lrotor          8.750 in      Lstator        9.080 in

2 Magnet Data:------------------------------------------------------------

Magnet    S-L 30MGO
Br            1.140 T         Hc           1100.000 kA/m    MuRec          1.020
CBr          -0.030 %/DegC    CHc            -0.220 %/DegC  DMag        8400.000 kg/m3
BrT           1.065 T         HcT           567.600 kA/m
Nuisance      0.000 in        BrTnu           1.065 T       MuRecnu        1.020

3 Control Data:-----------------------------------------------------------

RPM       15000.000 rpm       Vs            146.000 V       Drive        AC Volt
EMFCalc         BLV           delta          46.000 eDeg    Sw_Ctl     Generator

4 Winding Data:-----------------------------------------------------------

Connex          Wye
WdgType      Custom
Offset            3           CPP             1.000
Tph           2.000           PPATHS              4         SPP            1.500
Layers        1.333           CSidesPh           16         Z             48.000
MLT          24.344 in        LgthOEnd       10.929 in      Ext            0.000 in
EndFill       0.500           LaxPack        10.488 in      Liner      9.000E-03 in
WireSpec      SFill           SFg             0.400
NSH              70           WireDia         0.057 in      InsThick 1.150E-03 in
SFg           0.400           SFn             0.585         MaxSFn         0.870
Aslot         0.594 in^2      ASlotLL         0.560 in^2    ACond          0.178 in^2
GPAslot       0.598 in^2      ATstick         0.027 in^2    TopStick       false
TwjWid        0.079 in        TwjLeg          0.138 in      TwjThk         0.015 in
PhsWid        0.079 in        PhsLeg          0.138 in      PhsThk         0.000 in
ATwj      5.315E-03 in^2      APhs            0.000 in^2
XET           0.725           ETCalc        BDC 6.0         Rext           0.000 ohm
Nse           2.357           X_R             1.000         Ax1           35.000 mDeg
T_Wdg       240.000 DegC      Rph0        8.645E-05 ohm     R_LL       1.729E-04 ohm
T_c         240.000 DegC      Rph         8.645E-05 ohm/ph  TFRho          1.865
Inductances...
Lph       1.935E-03 mH        Mph            -0.001 mH      XL             1.000
```

```
Lg        1.061E-03 mH      LSlot     4.607E-04 mH      Lendt     4.132E-04 mH
Mg           -0.000 mH      MSlot        -0.000 mH      LDiff     1.013E-04 mH
Lsigma    9.752E-04 mH      Msigma       -0.000 mH      XLdiff        1.000
Lgg       4.604E-03 mH      Mgg          -0.002 mH      PCSlot        1.650
LL_d      5.066E-03 mH      LL_q      5.052E-03 mH      L_LL      5.059E-03 mH
Lg_0      9.600E-04 mH      Lg_2      2.362E-06 mH      Laa_d     1.938E-03 mH
Ld        2.533E-03 mH      Lq        2.526E-03 mH      Laa_q     1.933E-03 mH
Xd            0.016 ohm/ph  Xq            0.016 ohm/ph  Xsigma    6.847E-03 ohm/ph
XCd           1.000         XCq           1.000         Lext          0.000 mH
Gd            0.217         Gq            0.216         XLendt        1.000
kw1           0.925         Xm0           0.042 ohm/ph
ks1           1.000         kp1           1.000         kd1           1.000
ksg           0.907         fz            1.038         PSSlot     S-Closed
Saliency       Auto         CalcLdLq       Auto         muPlug        1.000
i1_Ang    -3877.139 A       i2_Ang     5940.122 A       i3_Ang    -2062.983 A

5 Magnetic Circuit Design:----------------------------------------------------

T_Mag       240.000 DegC    T_r         240.000 DegC    XBrT          1.000
BrT           1.065 T       BgOC          0.794 T       Hca         830.695 kA/m
BgAvOC        0.654 T       PhiG         11.501 mWb     BgA/BgOC      0.824
Bg1OC         0.964 T       PhiM1        10.792 mWb     Bg1/BgOC      1.214
BmOC          0.849 T       Bm/BrT        0.797         XBtpk         1.000
HmOC       -168.458 kA/m    Hm/HcT       -0.297         PC            4.010
Bst           1.783 T       Bsy           1.713 T       Bry           1.323 T
XTw           0.000         XSYoke        0.000         XRYoke        0.000
kT            0.120 Nm/A    kE            0.141 Vs/Rad  krpmNL       15.000 krpm
kSat          1.000         XSatn         1.000         CalcSatn      Fixed
Xks           0.000         ks            0.000         XTTarc        1.000
EffWst        0.280 in      EffLst        1.056 in      ukCL          0.000
XBgap         1.000         X_EMF         1.000         k_rpf         1.000
eLLpk       220.850 V       eTmax        44.934 V       Bslot        -0.000 T
IBk       10971.822 A       Bk            0.000 T       Hk         -830.695 kA/m
ILR       8.444E+05 A       BmLR        -73.117 T       HmLR      -5.79E+04 kA/m
IC180     2.122E+06 A       BmC180     -185.174 T       HmC180    -1.45E+05 kA/m
BHmag       142.993 kJ/m3   Carter        1.008         Xrm           0.500
Amhp         11.053 in^2    Aghp         11.354 in^2    Rghp      1.948E+05 At/Wb
Pm0           1.384 uWb/At  Xrl           1.000         prl           0.195
apEnd         1.000         Pend          0.000         Lme           0.260 in
u_LKG         0.000         f_Lkg         0.950         if_Lkg        1.053
Fringing         ON         XFringe       1.000         XBetaM        1.000

6 Constant AC Volts static performance [phasor diagram]:-----------------------

OpMode    Generating         Vs          146.000 V       RPM      15000.000 rpm
Tshaft      482.005 lbft    Pshaft    1.027E+06 W       Eff          98.975 %
WCu        4717.794 W       WFe        4696.362 W       WWF           0.000 W
WCan        330.452 W       WMagnet       0.000 W
WTotal     9744.608 W       TempRise    120.000 DegC    Jrms       5983.803 A/in^2
IWpk       6031.758 A       IWav       3839.912 A       IWrms      4265.097 A
ILpk       6031.758 A       ILav       3839.912 A       ILrms      4265.097 A
IDC_P      6958.953 A       WFeCalc          OC         Pelec     1.016E+06 W
Eq1          88.741 V       Vph1         84.293 V       VLL1        146.000 V
Iph1       4265.097 A       Is            0.000 A
Iq1        3830.506 A       Id1        1875.705 A       gammaACV     26.090 deg
Vq1          58.555 V       Vd1          60.635 V       delta        46.000 deg
Bg1Load       0.865 T       phi         -19.910 eDeg    PF            0.940
Bqad          0.000 T       Phida1        2.069 mWb     Phiqa1        4.204 mWb
BmLoad        0.670 T       Bma          -0.178 T       Fda1      -1172.083 At/gap
Tgap_PS     479.278 lbft    TEI_PS      478.827         Trel_PS       0.451 lbft
Tgap        479.645 lbft    Tei         479.194 lbft    Trel          0.451 lbft
Tloop       479.636 lbft
```

```
Vd0          207.572 V        Pelec     1.016E+06 W

8 Steady-State Thermal Model:-----------------------------------------------

TempCalc       DegCW          FixTMag       IterX          Ambient     120.000 DegC
DegCW      1.000E-02 degC/W   HTCcyl       10.000 W/m2/C   HTCend        0.000 W/m2/C
TempRise     120.000 DegC     T_c         240.000 DegC     T_r         240.000 DegC
T_f          240.000 DegC     T_y         240.000 DegC     HeatFlux      0.000 kW/m^2
SlotPeri       3.137 in       Liner     9.000E-03 in       ct_Liner      0.200 W/mC
SSArea        27.445 in^2     C_motor      84.069 kJ/C     ThRSlot   1.793E-03 C/W
FSArea       883.997 in^2

9 Miscellaneous:------------------------------------------------------------

Weights...
wt_Cu         33.437 lb       wt_Fe       111.158 lb       wt_Mag       14.225 lb
wt_Tot       158.821 lb       wt_Shaft    142.800 lb       wt_Frame     39.567 lb
wt_FeS        73.577 lb       wt_FeR       37.581 lb       wt_RSS      195.059 lb
Inertia components...
RotJ           0.356 kg-m2    RotJSS        0.358 kg-m2    RotJSh        0.176 kg-m2
RotJFe         0.120 kg-m2    RotJMag       0.060 kg-m2    LShaft       20.000 in
sigma          6.778 psi
Wf0            0.000 W        RPM0       1000.000 rpm      NWFT          1.000
Fringing          ON          XFringe       1.000          NHx              21
CanStyle       Rotor          SCanThk       0.020 in       SCanSecs          1
pc_SCan        2.500 %        pc_Mag        0.000 %        pc_Sh         0.000 %
Ecc            0.000          UMPavg    -1.88E-14 lb       UMPmax    4.769E-13 lb
TRFrms       213.228 lb       TRFavg      192.385 lb       TRFmax      261.647 lb
CForce     43182.709 lb                                    LamThk    6.000E-03 in
NLams           1415          pcLam         3.000 %        RFei      1.000E+06

10 Core loss analysis:------------------------------------------------------

WFeCalc           OC          LossFE         Mech          XFe           1.000
DFekgS      7480.246 kg/m^3   St.Steel Hiperco 50 (7mil)
DFekgR      7480.246 kg/m^3   Ro.Steel Hiperco 50 (7mil)
DFekgSh     7480.246 kg/m^3   Sh.Steel Hiperco 50 (7mil)
wt_Teeth      30.181 lb       wt_Yoke      43.397 lb       wt_Troot      6.358 lb
Specific core losses...
cFe_E60        0.053 W/lb     cFe_H60       1.254 W/lb     cFe_60        1.307 W/lb
cFe_E_F       14.643 W/lb     cFe_H_F      20.900 W/lb     cFe_F        35.544 W/lb
cFe_T_E       47.300 W/lb     cFe_T_H      28.044 W/lb     cFe_T        75.343 W/lb
cFe_Y_E       18.582 W/lb     cFe_Y_H      26.201 W/lb     cFe_Y        44.782 W/lb
Core loss analysis...
WFe_T_E     1728.267 W        WFe_T_H    1024.681 W        WFe_T      2752.947 W
WFe_Y_E      806.390 W        WFe_Y_H    1137.025 W        WFe_Y      1943.415 W


End of Design sheet---------------------------------------------------------
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